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NITRATES IN GROUNDWATER RESULTING FROM MANURE APPLICATIONS TO IRRIGATED CROPLANDS

by

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Field data were collected from experimental plots located near Grand Junction Colorado. Data collections were designed to provide a sufficiently broad range of conditions such that a simulation model could be verified. The experimental plots were planted to corn and were furrow irrigated. The basic management practices investigated were irrigation frequency, irrigation efficiency, and manure loading rate. Aimatological conditions, soil moisture, potential evapotranspiration, and irrigation system performance were measured in the field. Soil samples and percolation water collected immediately beneath the crop root zone were analyzed for various nitrogen species, total organic carbon, and common salinity cations and anions. Crop uptake of nitrogen was evaluated by periodic analysis of corn samples. Model simulations were ran for a wide range of typical Grand Junction conditions to evaluate the effect of irrigation and animal manure utilization practices on nitrate movement to groundwater.

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FOREWORD

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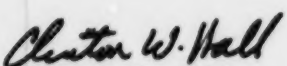
This project was initiated to investigate the behavior of animal manure in the soil environment of irrigated cropland and assess the impacts of irrigation and manure loading practices on ground water quality. This information is useful in establishing alternatives for managing the complex soil-water-plant environment to maximize the system's effectiveness as a treatment mechanism for animal manure. These alternatives can be incorporated in the development of best management practices for protecting the quality of both soils and surface and ground waters where animal manure is utilized in irrigated crop production situations.



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ABSTRACT

Field data were collected from 63 experimental plots located within a 9.3 ha area near Grand Junction, Colorado. Data collection activities were designed to provide a sufficiently broad range of conditions such that a simulation model could be verified. The experimental plots were planted to corn and were furrow irrigated. The basic management practices investigated were irrigation frequency, irrigation efficiency, and manure loading rate. Climatological conditions, soil moisture, potential evapotranspiration, and irrigation system performance were measured in the field. Soil samples were collected from the various plots and analyzed for nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), and the common salinity cations and anions. Samples of the percolation water immediately beneath the root zone were also collected and analyzed for the same constituents. Crop uptake of nitrogen (N) was evaluated by periodic analyses of corn samples.

An existing model describing the soil-plant-water-N system was chosen for evaluation. Proper N transformation rate coefficients were chosen for the field conditions, and the simulation model was applied to the experimental plots. Comparisons between measured and predicted NO_3-N distributions, organic nitrogen (Org-N) distributions, soil-water distributions, organic carbon (Org-C) content, and crop N uptake are presented. Also, NO_3-N concentrations measured in extractor samples are contrasted with those predicted by the model for the 120 cm depth. Taken as a whole, the model predictions compare favorably with the measured values for these parameters.

Model simulations were run for a wide range of typical Grand Junction conditions to evaluate the effect of irrigation and animal manure utilization practices on NO_3-N contamination of groundwater. The results indicate the time required to reach a steady-state condition and the quantitative effects of irrigation efficiencies, irrigation frequency, manure loading rates, manure loading frequency, and initial soil organic matter conditions. The model was also used to test the effects of control practices on salt build-up and movement.

This report was submitted in fulfillment of Grant No. R-804827 by Colorado State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period October 1, 1976 to August 31, 1980, and the work was completed as of October 1, 1980.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ASMD	-- allowable soil moisture depletion
CNU	-- cumulative nitrogen uptake
COD	-- chemical oxygen demand
E_a	-- irrigation application efficiency
E_{tp}	-- potential evapotranspiration
FGS	-- fraction of growing season
FTNU	-- fraction of total nitrogen uptake
IRF	-- irrigation replacement fraction
Org-C	-- organic carbon in manure or soil
Org-N	-- organic nitrogen in manure or soil
TKN	-- total Kjeldahl nitrogen measurement
TOC	-- total organic carbon measurement
TON	-- total organic nitrogen in soil and manure
TNU	-- total nitrogen uptake

SYMBOLS

C	carbon
C_{av}	total available carbon
Cl^-	chloride
C_3	NO_3-N solution concentration
C_4	NH_4-N adsorbed-phase concentration
G	gaseous nitrogen
g_w	denitrification dependence on soil-water content
K_{co}	crop growth stage coefficient
K_D	ion exchange partition coefficient
k_{ci}	first order carbon transformation rate coefficients
k_j	first order nitrogen transformation rate coefficients
N	nitrogen
N_m	resistant manure nitrogen
N_s	mineralizable soil nitrogen
N_x	readily mineralizable manure nitrogen
NH_4-N	ammonium nitrogen
NO_3-N	nitrate nitrogen
q	soil-water flux
t	time
θ	volumetric soil-water content
ρ	soil bulk density

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Bruce E. Kroeker

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SECTION 1

INTRODUCTION

BACKGROUND

Loehr (1968) estimates that excremental animal manure exceed human wastes by an order of magnitude each year in the United States. For the feeding operations that are increasingly using confinement systems, the large manure volume creates a sizeable disposal problem. Land application of animal manure has been used as a fertilization practice for thousands of years and remains today as the cheapest and most common manure disposal alternative. Most land surfaces used for applying manures are agricultural croplands, many of which require irrigation to supplement natural precipitation.

Animal manure contains a variety of salt and organic materials that easily dissolve or suspend in water and thereby degrade the quality of the water. Two broad water quality detriments can be defined relative to the spreading of manure over agricultural lands. First, precipitation and irrigation overland flows erode surface materials including the organic and mineralogical components of the manure and transport them to nearby receiving waters such as streams, lakes and reservoirs. The nutrients can lead to eutrophication and the salts to toxic impacts on native biota. The second problem centers on the infiltration of water through the soil toward groundwater basins. Soluble nitrogen (N), carbon (C), and salt constituents are transported downward by the water and are partially transformed by the soil and its microbial population. In both aspects of this environmental problem, the control of the water movement through improved irrigation and tillage practices can substantially reduce the detriments.

The least understood problem is the management of irrigation and land disposal systems in conjunction with an objective of groundwater quality control. The pollutants move slowly toward the groundwater basin and undergo complex transformations. Notable examples exist where nitrate-nitrogen (NO_3-N) levels in groundwater systems are increasing to critical levels 10 to 20 years after the cessation of an animal feeding operation close to the well or monitoring point. Although too late for effective action for these situations, many other actual or planned disposal sites can be managed so that the long-term consequence will be minimal. It is necessary that the hydrologic, chemical, and biologic processes operating in the system be understood in relation to the manageable variables so that an integrated evaluation of the disposal problem can be made.

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SCOPE OF STUDY

The technical literature does not describe many studies in which the manure application, irrigation, and groundwater systems are investigated collectively. This study was proposed to evaluate the effects of various irrigation practices and manure loading rates on the movement of pollutants toward groundwater basins. Neither time nor funding allowed an assessment of this problem on a wide geographical scale. Consequently, it is important to note the scope of this project.

This study was conducted on a 9.3 ha experimental site near Grand Junction, in western Colorado. Experimental plans, which will be described in detail later, called for an intensive sampling and monitoring schedule that resulted in a volumous array of field data. Coupled with the size of the data base was the large spatial and temporal variability that can be expected from any field scale experimentation. These problems were felt to be best suited to a simulation modeling framework of study as the most effective means of reducing the large amount of data and its variance to useful comparisons of the system inputs and responses. The study was thus designed to provide a range of conditions broad enough to verify a simulation based on mathematical descriptions of physio-chemical-biological processes. The model resulting from this work could then be used to evaluate alternative management practices as long as the range of conditions for which it had proven reliable was not exceeded.

The scope of this study was necessarily limited by time, space and funding. Of the variety of animal manures being applied to irrigated lands, only yearling beef cattle manures were studied. Because of primary interest being placed on the groundwater impacts of land disposal practices, the surface runoff component was minimized by incorporating the manure into the upper 20 cm of the soil and controlling the field tailwater runoff rates. The field was planted to corn and was watered with conventional furrow irrigation practices common in the western United States. Thus, alternative manures, application procedures, crops and irrigation methods were not investigated.

Utilizing a single field location also imposed limitations on the scope of a research effort. Grand Junction is located in an arid mountain valley characterized by high summer temperatures and low winter temperatures. The growing season lasts from about April to October, and agricultural production is heavily oriented toward the livestock industry. Soils are naturally saline due to their marine origin, but irrigation water quality is good. The annual precipitation of about 20 to 25 cm does not significantly affect the agricultural system but limits manure spreading and major cultivation practices to either late fall or early spring. For this study, manure loadings were applied each spring.

Attention was focused primarily on the N system. NO_3-N is one of the major pollutants affecting groundwater quality when manures are applied to irrigated lands. There are, of course, a number of pollutants derived from the manure that are also important. Salts, organic compounds, and viral or bacterial organisms are common examples. As the materials decompose, N is

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released to the soil profile through a series of complex biological transformations that are partially manageable. The movement of the end product NO_3-N can be potentially minimized by controlling downward water movements and creating conductions conducive to plant uptake and denitrification. Thus, the scope of this study was centered on a better understanding of how to optimize irrigation and manure management practices to control groundwater NO_3-N levels.

PROJECT OBJECTIVES

The principal objective of this project was to investigate the behavior of manures in the soil environment of irrigated cropland and assess the impacts of irrigation and manure application practices on groundwater quality. This objective was proposed with a view toward establishing guidelines for managing the complex soil-water-plant environment to maximize the effectiveness of the system as a treatment mechanism.

To accomplish the overall objective of this study, five specific activities were outlined. These are as originally written in the project work plan:

1. Integrate a detailed simulation package for evaluating the effects of different irrigation systems and their operation on the movement of water, salt, and nutrients (especially N) within the root zone (these models would be primarily but not limited to improved versions of those currently available);

2. Test the various process models for their sensitivity toward input data and basic assumptions in order to develop guidelines for their use in other applications and to suggest the format and scope of data collection activities;

3. Optimize the design and management of irrigation systems to maximize N "consumption" (crop uptake, denitrification, and immobilization) while minimizing the downward flux of salts and NO_3-N;

4. Collect detailed field data for the verifications of the simulation systems needed to extend the results of this project to other climates, soils, and manures; and

5. Formulate general recommendations for irrigation of agricultural lands where manures are applied.

During the course of this study, efforts dealing with the simulation modeling and field data collection were given the most emphasis. Although careful attention was given to collecting and analyzing data, natural field variability was very large and it was difficult to assess the results of the study until substantial model analysis had been completed. The third objective required that the model parameters relating the conditions manageable by the farm operation and the responses of the system be systematically optimized. In the truest sense of the term optimization, the investigators were not able to accomplish the objective because of computer limitations.

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However, the results of this project can be used to evaluate the irrigation and manure application system alternatives which one might choose at the planning stage.

REPORT OVERVIEW

In addition to the volumous amounts of data that were collected, this study resulted in two Ph.D. dissertations and one M.S. thesis relating to mathematical descriptions of the various hydrologic and biochemical processes that will be summarized in this report. All of this information cannot be included in this report because of a need to limit the space to a summary of the project results. As a consequence, the reader interested in a more detailed discussion of the analytical procedures used to generate the results contained herein is referred to Gerards, 1978; Boonyatharokul, 1979; and Kroeker, 1980.

Sections 2 and 3 enumerate the project conclusions and recommendations, and Section 4 is presented to summarize the experimental and analytical approaches. The simulation model is briefly discussed in this section, and then its effectiveness in representing three years of field data at Grand Junction is given in Section 5. As stated in the conclusions, the results indicate that the model can be used as a management tool. Section 6 describes the modifications made to the model to make it a tool that can be used to assess irrigation and manure loading management alternatives. An extensive array of conditions was studied in the management context and is discussed in Section 6. These results indicate some basic practices that should be followed when disposing of manures on agricultural lands while attempting to protect the quality of an underlying groundwater resource.

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SECTION 2

CONCLUSIONS

A computer simulation model reported by Rao et al. (1980) was tested with three years of field data from an irrigated site near Grand Junction, Colorado, where variable applications of yearling beef cattle manure had been made. With adjustments to the rate coefficients for the mineralization of the manure organic-nitrogen (Org-N) to ammonium-N (NH_4-N) and NO_3-N, the model predicted the measured conditions within 10 to 25 percent for more than 80 percent of the total data base. Since individual components of the model have been verified elsewhere under other soil, crop and climatic conditions, it is concluded that it represents a usable and effective analytical tool.

The mathematical and conceptual sophistication of the model is congruent with the expertise of practicing engineers and soil scientists. Technical personnel charged with evaluating groundwater NO_3-N pollution from irrigated and/or rainfed lands where animal manures are being disposed of can utilize this model. Input data are easily collected as part of routine monitoring and evaluation studies. The model is also a useful research tool, particularly where the scope of investigation incorporates large time and spatial scales.

An analysis of several irrigation and manure management practices for two widely different soil conditions delineates a number of conclusions regarding these practices.

The most important irrigation of the season in moving NO_3-N toward a groundwater system is the first water application. In most surface irrigated conditions, at least 50 to 75 percent of the annual deep percolation comes from the preplant or emergence irrigation. Subsequent irrigations occur when the soil surface exhibits a lower infiltration rate and the crop root zone is active to a greater depth. For the Grand Junction soil, a soil with a high organic content, improving the first irrigation from a typical 24 cm application to a 12 cm application reduced the annual N flux below the 200 cm depth by more than 50 percent. Similar results were obtained for a soil with 20 percent of the initial soil Org-N content.

The frequency of irrigations also indicated a significant effect on N leaching. Irrigating when the soil moisture had been depleted to 15 percent by crop uptake reduced the flux by 30 to 35 percent over a frequency based on 60 percent depletion, but nearly all of this effect is attributable to irrigation efficiency rather than impacting the N transformations. The wetter the soil the easier it is to control the fraction of applied water percolating below the root zone of the crop.

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Manure applications on irrigated lands increase N losses from the system by both denitrification and leaching in direct proportion to the loading rates. For the Grand Junction soil conditions, increasing the wet weight application rate from about 12 metric tons/ha (MT/ha) to 404 MT/ha increased denitrification losses by 900 kilograms-N (kg-N)/ha/yr and leaching losses to the groundwater basin by 360 kg-N/ha/yr. The effects on a low organic soil (20 percent of Grand Junction soil values) was proportionally the same.

Probably the most interesting conclusion regarding the loading management is the effect of application frequency on the N losses due to denitrification and leaching. Applying manures each year, every other year, and every third year over an extended period results in very small changes (about 10 percent) in the amount of N leached from the 200 cm profile. The losses due to denitrification on the other hand are reduced significantly by less frequent loadings. Consequently, as a disposal practice, manure applications should be made annually in order to maximize the treatment efficiency of the soil-crop system.

The salts in the manure applied to irrigated lands create conditions detrimental to efforts aimed at controlling N contamination of groundwater resources. Heavy loadings and efficient irrigation practices will result in very large accumulations of salts in the soil profile between 40 and 120 cm and therefore will seriously affect crop yields. The same heavy loadings coupled with traditional irrigation practices still result in salination of the soil profile below 60 cm but do not tend to accumulate salts beyond a level dictated by the annual leaching fraction.

As a final conclusion, a statement is made concerning the time frame that must be considered in evaluating manure management practices. The simulation model indicates that steady-state conditions in the first 2 m of a soil profile are not reached until at least five to six years following the initiation of a disposal operation. NO_3-N levels in the drainage system at the field study site were not significantly different than those of the previous five years of study which support this conclusion. For deeper soil profiles or where the groundwater lies much deeper below the surface, the effects of manure disposal are not likely to be indicated for many years. If the irrigation practices are maintained at high efficiency levels, the impacts may not be indicated within the design life of the irrigation system. Thus, monitoring commitments must be made on five to ten year periods rather than the one to three year periods encompassed in research investigations.

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SECTION 3

RECOMMENDATIONS

The effects of animal manure additions to the upper soil profile on the decomposition of soil and organic materials under field conditions need further attention in the model reported by Rao et al. (1980). The modification in the mathematical forms of the model should probably be made in the mineralization rate coefficients. The rate coefficients reported by Rao et al. (1980) for other N and C transformations worked well for the Grand Junction conditions and were also verified for other conditions. However, it is recommended that additional field research be conducted to further define mineralization rate coefficients.

Controlling the applied depth of irrigation water during the first irrigation should be the most emphasized irrigation practice in managing the contribution of N to underlying groundwater basins. Irrigating more frequently should also be considered as one method of controlling N leaching. Conversion from surface irrigation to sprinkler irrigation systems should be considered where the problem is particularly acute since water applications are substantially more manageable.

Annual manure loadings should be encouraged over less frequent applications where disposal rather than fertilization is the primary objective of the program. Careful evaluation of the salts contained in the manures should be made if crop production is to be maintained, particularly if high irrigation efficiencies can be achieved consistently. As a future research study, it should be possible to optimize the manure management practice by considering the economic trade-offs between crop production and groundwater pollution.

Environmental monitoring at field disposal sites should be long-term programs in order to effectively safeguard groundwater quality. The design of a disposal project should be based on allowable levels of NO_3-N input to the groundwater basin, and this will require the coupling of a model such as the one used in this study with a model of the groundwater system itself.

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SECTION 4

EXPERIMENTAL AND ANALYTICAL APPROACH

INTRODUCTION

Although the scope of this research is limited to a single combination of geographical conditions, manure characteristics, irrigation methods, soil types, and cropping patterns, a wide range of conditions affecting the movements of manure end products was achieved within the soil environment. Three basic management parameters were selected to develop these soil conditions: (1) the frequency of irrigations; (2) the efficiency of irrigations (leaching fractions); and (3) the manure loading rates.

Irrigation frequency controls the mix of moisture and air in the soil. Frequent irrigations create an environment of high average moisture contents and low average air contents, and thus, directly affects the relative proportion of aerobic and anaerobic microbial populations. It is therefore, at least conceptually possible to change the relative rates not only of the individual N transformations but also the relative magnitudes of the transformations themselves.

Irrigation efficiency is a qualitative term describing the ratio of irrigation water used in satisfying evapotranspiration needs to the water directed for the purpose of irrigation. A specific subunit of irrigation efficiency is a modified application efficiency (E_a) defined as the fraction of water entering the soil profile that is consumptively used by the crop. The fraction of irrigation water percolating below the root zone is one minus E_a. Varying the amount of deep percolation changes the transport mechanism of solutes in the soil system.

The rates of manure loadings strongly influence the N balance. Not only is the manure a primary source of N but also the principal source of the C energy source needed for the various transformations. Loading rates affect the physical properties of the soil as well as the nutrient status of the crop root zone, thereby influencing water movements and crop uptake.

EXPERIMENTAL FACILITIES

In 1973, a 9.3 ha area consisting of three irrigated fields north of Grand Junction, Colorado, was leased to develop a field-scale research facility (Figures 1 and 2). The first investigations dealt with the effects of irrigation practices on irrigation return flow salinity and crop yields. The development of the site is described in detail by Skogerboe et al. (1979a,

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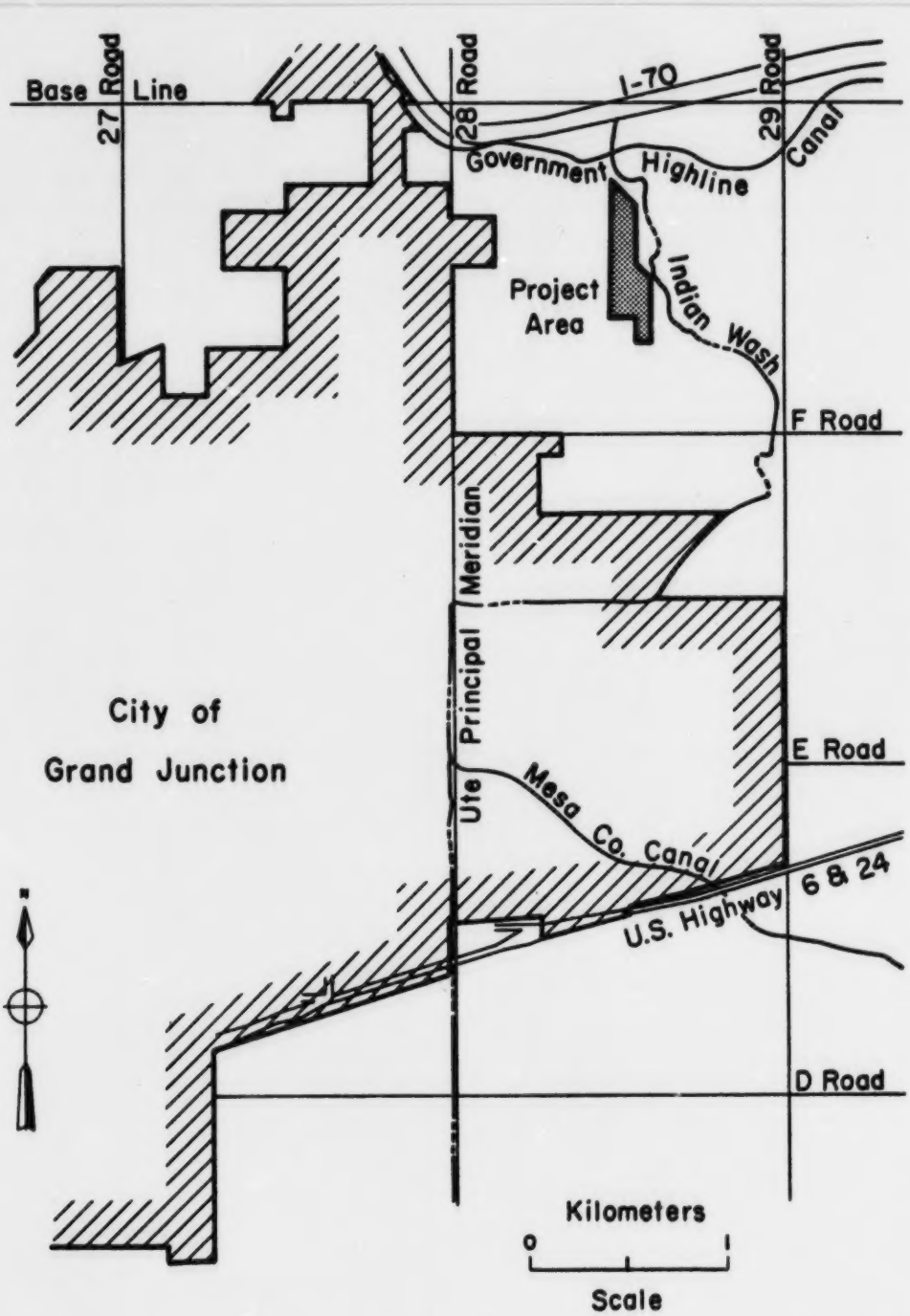

Figure 1. Location and setting of experimental site.

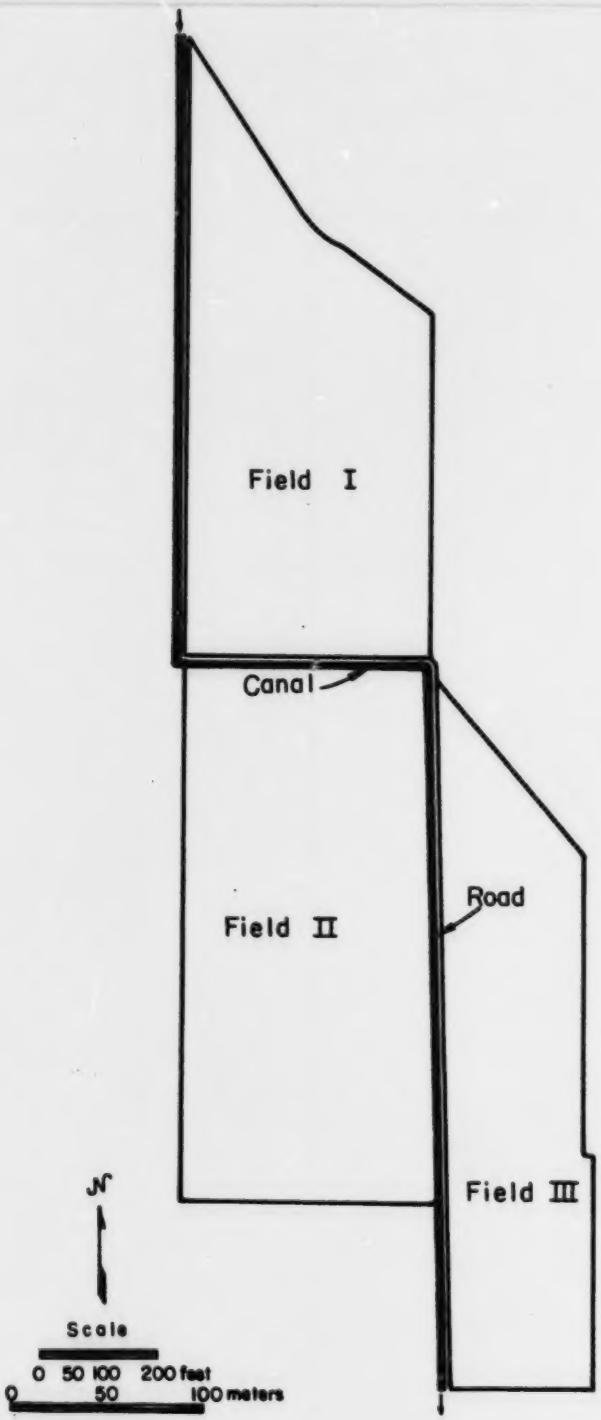

Figure 2. Field layout of the experimental site.

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b), including photos of the construction process and the operation of the system.

Within the three fields, 63 plots were separated from each other and from the surrounding area by individual drainage systems and an impermeable plastic barrier around the plot perimeters. Water applied to the surface of a plot was contained within the confines of the plastic barrier on the sides and a solid shale formation underlying the soil profile. Data describing irrigations, evapotranspiration, drainage, and soil moisture storage allow a mass balance to be made of water and constituents on a plot-by-plot basis.

The first investigations ended in the fall of 1976. Continued use of the facility for this investigation followed a renewal of the lease agreement. Modifications to the site were made to be more consistent with the design of this project data collection program. The irrigation water supply was consolidated from four separate diversions to a single point near the northern end of the farm and nine plots were abandoned in Field III. The gated pipe irrigation system was organized to irrigate the plots in blocks of three rather than individually, and five new plots were organized in Fields I and II to be used as experimental controls. These plots adjoined the constructed plots but did not have separate drainage systems or surrounding barriers.

A soil-water chemistry laboratory located in a federal complex south of Grand Junction which emphasized salinity analyses was moved to the field site and was housed in a temporary structure built by project personnel. Laboratory analytical capabilities were expanded to handle analyses of the various N and C constituents in soil, water and plant samples.

Many of the actual farming operations such as plowing, planting, cultivation and harvesting were handled by the landowner in return for the crop. Other operations such as irrigating and clean-up were accomplished by project personnel. The irrigation water came from the Colorado River via the Government Highline Canal. The drainage waters and field tailwater were diverted directly to a natural wash running along the east side of the site.

EXPERIMENTAL DESIGN

The design of data collection activities for this study involved three irrigation frequencies, three irrigation efficiencies, and three manure application rates. In addition, manure applications were divided into three frequencies: each year, every other year, and once at the project beginning. The field site consisted of 54, 30 x 30 m lysimeter plots and nine rectangular plots. In order to match the various treatment combinations to the availability of the square plots, only one replication of treatments was possible and the manure application frequencies were not completely developed. Seven of the plots were not given manure loadings to act as controls.

Figures 3 to 5 show the combination of treatments studied. Plots 17-28, 32, 34, and 36 and 37-48 were given three levels of manure loadings at the project start and were irrigated with each combination of frequency and efficiency. Plots 31, 33, and 35 in Field II, all of the plots in Field I except NP, 3, and 7, and plots 49-51 in Field III were scheduled to receive

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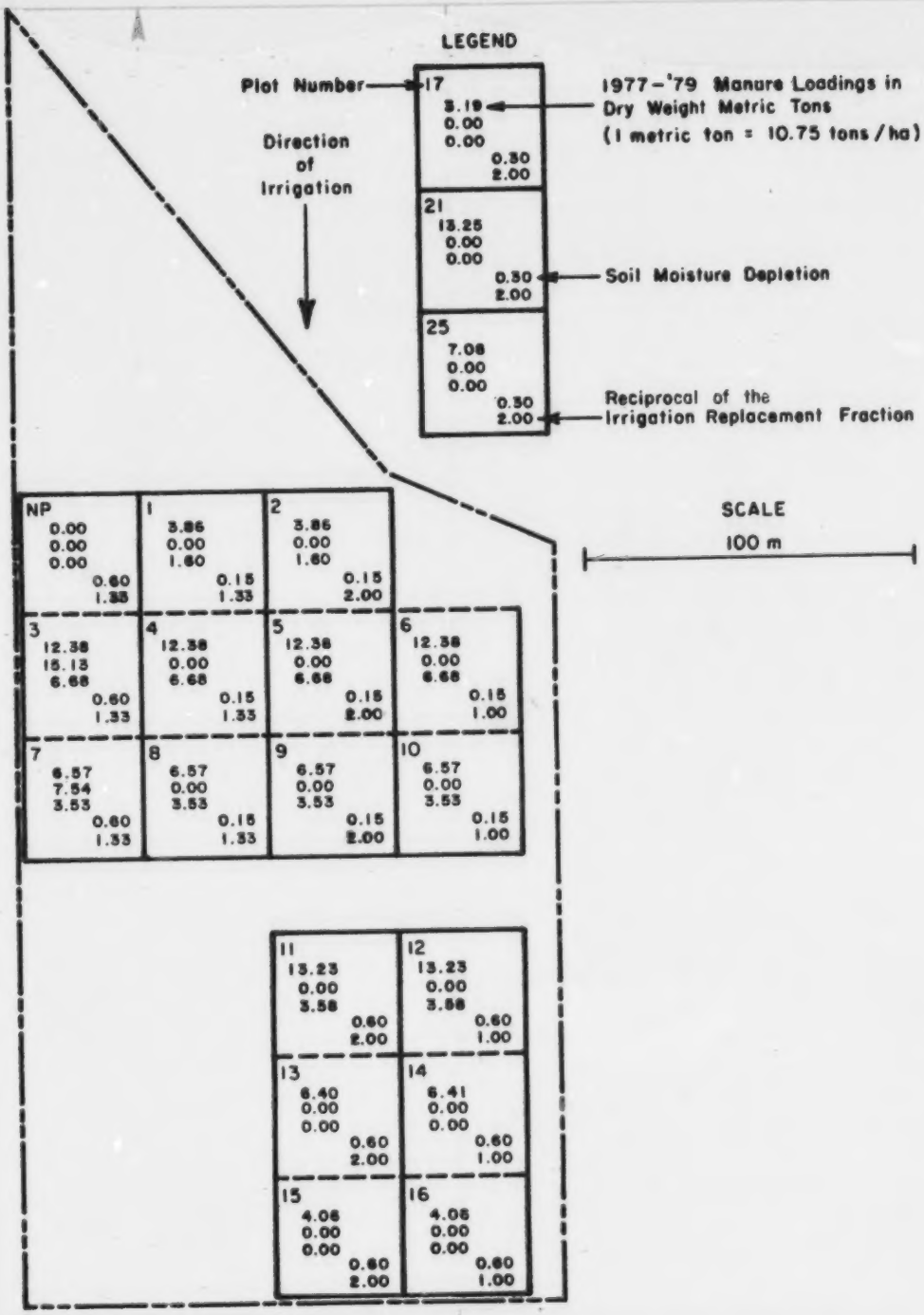

Figure 3. The organization of irrigation frequency, irrigation efficiency, and manure loading treatments in Field I.

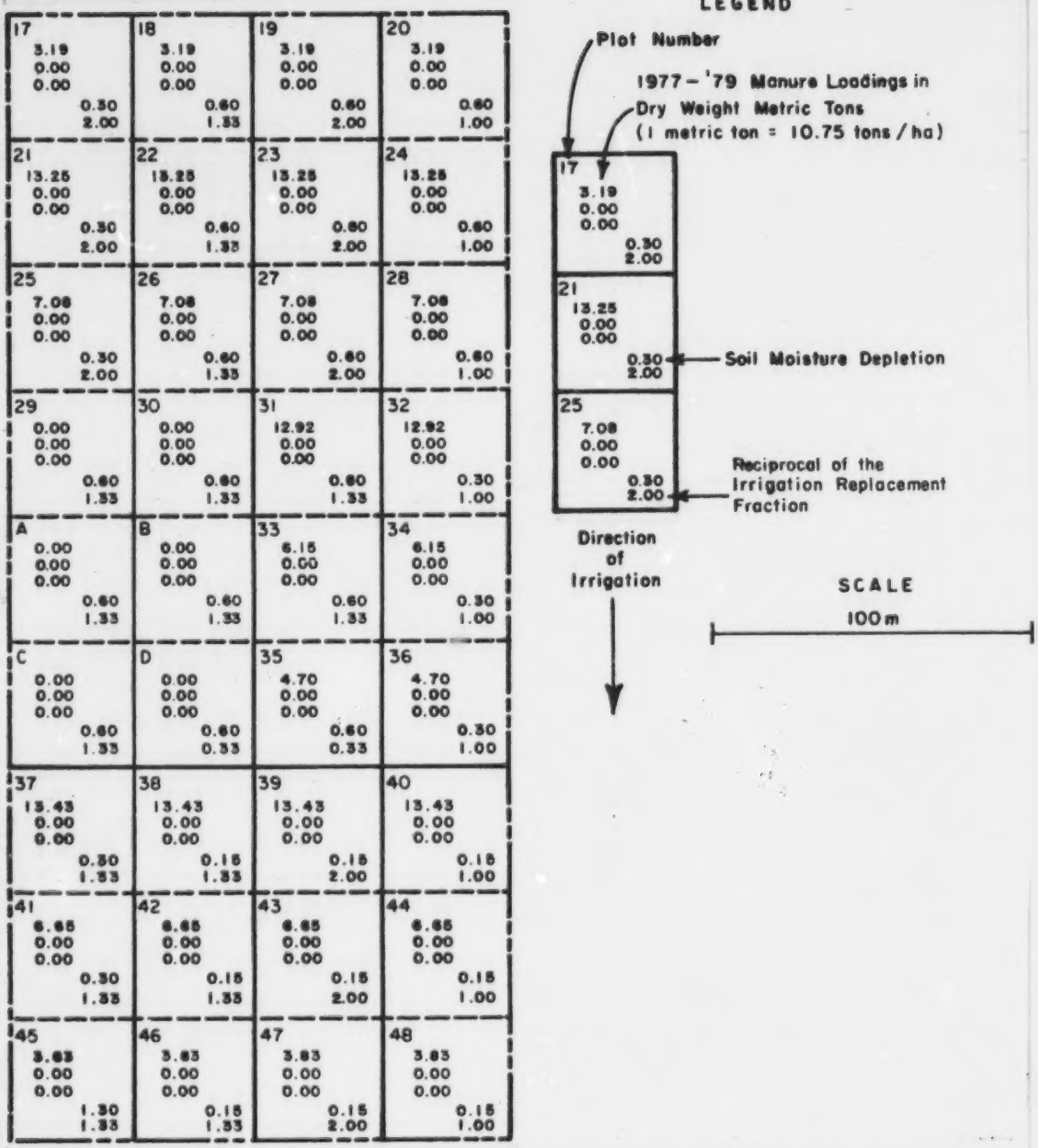

Figure 4. The organization of irrigation frequency, irrigation efficiency, and manure loading treatments in Field II.

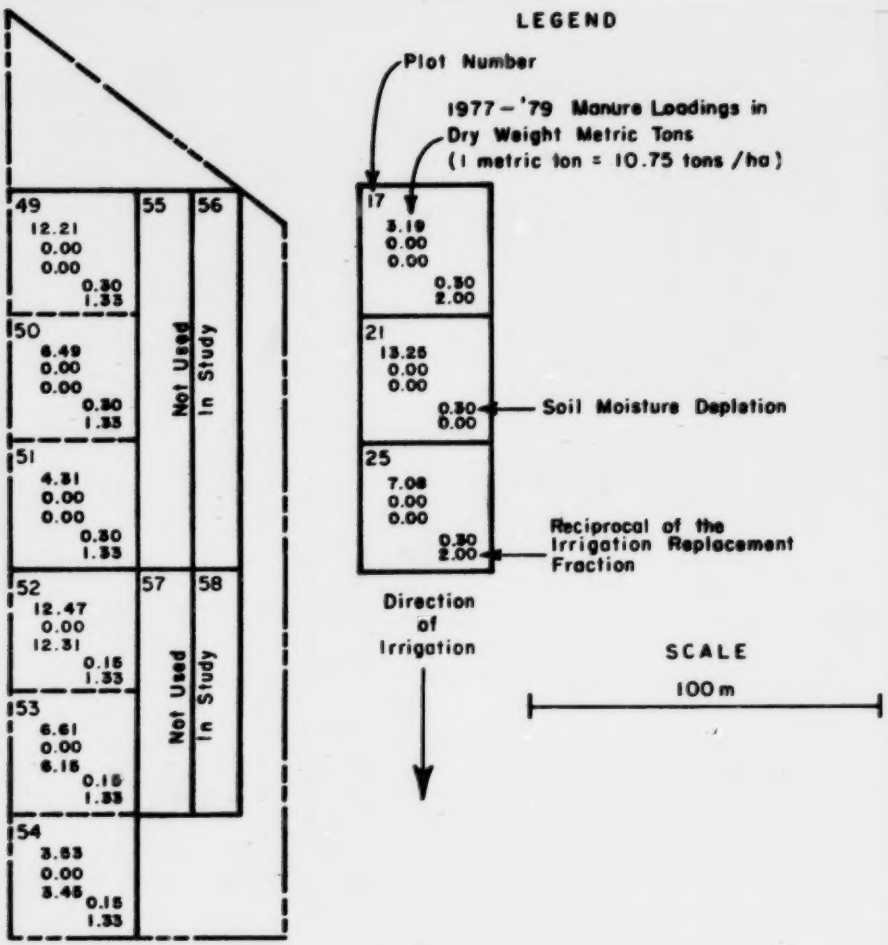
LEGEND
Plot Number
1977 – '79 Manure Loadings in Dry Weight Metric Tons (1 metric ton = 10.75 tons /ha)
Soil Moisture Depletion
Reciprocal of the Irrigation Replacement Fraction
Direction of Irrigation
SCALE
100 m
Not Used In Study
Not Used In Study

Figure 5. The organization of irrigation frequency, irrigation efficiency, and manure loading treatments in Field III.

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the three manure loadings during the first and third years. Unfortunately, equipment failure by the supplier in the spring of 1979 forced the planting and growing season to begin before this series of treatments could be applied. The plots NP, 1 and 7 in Field I and plots 52-54 in Field III were scheduled to receive loadings each year but were also incomplete due to the 1979 supplier problem. Although not as comprehensive as originally intended, the range of conditions was left basically intact and allowed the study to achieve the original objectives.

Irrigation Frequencies

The frequency of an irrigation system is governed by how much of the total available moisture in the root zone is allowed to be depleted before the next irrigation. The total available moisture is defined as the product of bulk density, root depth, and the difference between field capacity and wilting point expressed on a dry weight basis. Standard practices for surface irrigated systems vary somewhat but are generally based on about 60 percent depletion of the available moisture. Sprinkle and trickle irrigated systems are generally designed on a lower allowable depletion (10-40 percent) in order to minimize pumping, pipe and emitter costs.

The three irrigation frequencies selected for this study were based on 15, 30, and 60 percent depletion levels. The frequency of irrigation in days, is the allowable depletion times the total available moisture divided by the average evapotranspiration rate. At the Grand Junction site during July and August, these depletions corresponded to irrigation frequencies of about 3 to 12 days. The higher frequencies were intended to simulate sprinkle and trickle irrigation conditions.

Irrigation Efficiencies

The irrigation literature abounds with definitions describing irrigation efficiency. This study was primarily interested in the ratio of water depths percolating below the root zone to the total infiltrated depth. A recent definition by Martin and Watts (1980) called "irrigation replacement fraction" (IRF) appeals conceptually to the writers and is consistent with E_a mentioned earlier. The IRF is the depth of irrigation water required to replace the average soil moisture depletion divided by the depth actually applied. The levels of IRF utilized were 1.0, 0.75, and 0.50. These ratios corresponded to leaching fractions of 0, 0.25, and 0.50, respectively. In other terms, the amount of water added to the root zone was from one to two times the irrigation water needed.

The three levels of irrigation efficiency described above represent the range of values typical of most irrigation systems. Few if any actual systems achieve an IRF = 1 consistently because it is difficult to irrigate uniformly, and soil moisture depletion is spatially varied. Although the irrigations in this study were carefully controlled, the IRF = 1 condition could only be approached.

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Manure Loading Rates

The manure loading rates utilized in this study were based on wet weights. A loading rate of 200 MT/ha was selected from values reported in the literature as being typical of heavy rates. Although some studies have investigated rates up to 300 to 400 MT/ha, these rates are generally intended to create severe soil conditions not often found in practice. The second loading rate in this project was set at about 100 MT/ha to correspond with rates common in the project area. To include a rate below usual practice, the third rate was set at about 50 MT/ha. The values shown in Figures 3 to 5 are rates based on a dry weight basis and vary due to differences in moisture content in the manure over the three years they were applied.

The beef manure used in this study was analyzed at the time of application by sampling each load as it was delivered and spread. Table 1 gives a summary of the 1977 average chemical breakdown of constituents on a dry weight basis. Fewer data were taken in 1978 and 1979 but were not found to vary significantly from 1977 characteristics. These manure samples were tested in the analytical facilities of the Natural Resources Ecology Laboratory at Colorado State University and the U.S. Environmental Protection Agency laboratory at Ada, Oklahoma. The comparisons shown in the righthand column of Table 1 indicate the average result ratio for the two laboratories.

FIELD DATA COLLECTION

The conditions at the test site were monitored during the study by directly measuring parameters in the field and by collecting soil, water, and plant samples for laboratory analyses. Direct measurements included climatological conditions, soil moisture, potential evapotranspiration (E_{tp}), irrigation system performance, and surface and groundwater flows. Samples of irrigation water, field tailwater, percolation directly beneath the root zone, and drainage flows were collected and evaluated in the laboratory for the salinity constituents, NO_3-N, and NH_4-N. Some tests were tried to isolate forms of organic carbon (Org-C) and Org-N which were soluble, but the tests did not have the sensitivity to detect the very small quantities present. Soil samples were collected from the various plots and were evaluated for the parameters noted above plus TKN and TOC. To segregate field conditions or simulated field conditions from laboratory measurements, the term Org-C will be used to describe TOC in the field and TOC will be used exclusively when referring to laboratory data. Periodic crop samples were taken to evaluate the uptake of N in the above-surface plant parts during the irrigation season. Corn samples from all plots were evaluated at harvest. Nearly all of the results were recorded and reduced by computer.

In the subsections that follow, a brief review of these field data collection activities will be described.

Field Measurements

In the southwest corner of Field I, a small area of alfalfa was maintained to create typical irrigated conditions around a weather station set up to measure precipitation, U.S. Weather Bureau (USWB) Class A pan evaporation,

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TABLE 1. SUMMARY OF MANURE CHARACTERISTICS DURING 1977

Constituent	Average composition (% dry weight)	Standard deviation	CSU/EPA comparison
Dry Matter (DM)	66.68	7.51	1.06
Volatile Solids (VS)	63.74	6.48	0.99
Five-Day Biochemical Oxygen Demand (BOD_5)	2.57	0.63	--
TKN	2.24	0.24	0.95
NH_4-N	0.30	0.11	0.78
Total Inorganic Nitrogen (TIN)	0.30	0.11	--
Total Carbon (TC)	28.2	6.9	0.93
TOC	26.7	3.3	--
Total Phosphorus (TP)	0.19	0.02	0.34
Orthophosphate (Ortho-P)	0.03	0.01	0.15
Calcium (Ca)	2.96	0.35	0.80
Sodium (Na)	0.67	0.09	0.43
Magnesium (Mg)	0.85	0.10	1.16
Potassium (K)	2.13	0.29	1.11
Chloride (Cl)	1.65	0.22	1.01
Iron (Fe)	0.43	0.11	1.28
Copper (Cu)	0.0016	0.0003	0.81
Manganese (Mn)	0.015	0.002	1.13
Zinc (Zn)	0.012	0.001	1.29
Chemical Oxygen Demand (COD)	3.51	0.88	--

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and atmospheric temperature. All of the weather station equipment was commercially available products in common use and yielded readings consistent with the USWB station about 2 kilometers (km) north of the site. Some of the measurements such as solar radiation and wind run were compared to similar measurements by USDA studies about 15 km west of the project site.

Irrigation water was diverted into an aluminum pipeline at the northern edge of Field I and continuously monitored with several strategically placed in-line propeller meters. At each takeoff to gated pipe serving the various plots, the flow was passed through an elevated pair of V-notch weirs. The weirs were contained in a stand consisting of a pipe to open-tank transition from the supply pipe, a rock baffle to quiet the flow, the weir plates, and then a tank to pipe transition to the gated pipe. When diverted from the gated pipe, it was important early in the project to establish the hydraulic characteristics of the furrow irrigation system, which entailed measuring the inlet furrow flows and tailwater using small trapezoidal and cutthroat flumes. Aggregate flows leaving each plot were measured with Parshall flumes equipped with continuous stage recorders. Together these measurements led to an accurate assessment of the mass balance and temporal distribution of the surface flows. The water percolating through the soil and that being utilized by the corn crop required indirect evaluation. Once the drainage water reached the end of the vertical profile, the flows were reflected in the drainage system discharge. These flows tended to be fairly stable and were measured periodically with stop watches and calibrated containers.

The evaluation of the furrow irrigation system noted above was necessary to investigate the uniformity of irrigation applications. In addition to the inflow-outflow furrow stream size measurements, other measurements included cross-sectional areas along the furrow before and after irrigation, rate of advance and recession, flow depths, and ring infiltrometer tests. The results of these tests are described by Gerards (1978). These tests provided the information needed to select furrow stream sizes on the plots which would irrigate the three plot sections uniformly.

Soil moisture levels in the plots were monitored during the first two years of the study using a neutron probe and during the third year by gravimetric sampling. For the neutron readings, small aluminum tubing sealed at the lower end was placed in two locations within each plot. The tubing lengths were precut to extend from the soil surface to the solid shale formation underlying the plots. Readings were taken before and after each irrigation and at the time soil samples were collected for chemical analysis.

The final type of field measurement taken directly in this study is probably the most important--the measurement of E_{tp}. It has become general irrigation engineering practice to simulate the consumptive water use of a particular crop at a specific growth stage and soil moisture condition in the following steps. First, E_{tp} is defined on the basis of a reference crop, growing under plentiful water and nutrient conditions and shading at least 80 percent of the soil surface. Alfalfa is the common reference crop in the western United States and was used in this study. The second step is to define a crop growth stage coefficient (K_{co}) describing the relationship between E_{tp} and the evapotranspiration of the crop under well-watered and

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well-fertilized conditions. This temporarily distributed coefficient has been given considerable attention for field corn production and has been verified for the Grand Junction conditions (Kruse et al., 1977). The third step is to adjust the well-watered evapotranspiration rates for soil moisture stress conditions. Although several functions are found in the literature, a more specific function was derived for this study. In a later section describing the simulation model, a more explicit description of the soil moisture stress adjustment is given.

The field experiments were started in the late summer of 1977 when two identical hydraulic weighing lysimeters 1.18m x 1.18m x 1.07m, shown schematically in Figure 6, were installed near the weather station in the small alfalfa area of Field I. Both lysimeters were filled with well-mixed Billings Silty Clay loam common to the site and planted to alfalfa in mid-season 1977. At the beginning of the 1978 season, the alfalfa was cut early and both lysimeters were well irrigated. Then irrigation on one lysimeter was completely stopped until the plants neared a permanently wilted condition throughout a 24-hour period. The other lysimeter was irrigated frequently to yield E_{tp}. The data from both lysimeters were compared and used to develop a simulation model for E_{tp} and a model of soil moisture stress effects (Boonyatharokul, 1979; and Boonyatharokul and Walker, 1979). During the 1979 irrigation season, both lysimeters were operated to yield E_{tp} data which were used to schedule irrigations on the plots.

Field Sampling

The chemistry of soil, water, and plant systems was identified throughout the project by collecting samples for laboratory analyses. Soil samples before and after the cropping season were taken in 30 cm increments over the entire soil profile using a trailer mounted soil probing rig and by hand auger to a depth of 150 cm during the growing season. Samples were collected from five to eight locations on a plot and then aggregated for the first 30 cm sample. Below 30 cm, samples were collected from two plot locations and were consolidated. The samples were then oven dried at 65°C, ground, and evaluated in the field laboratory.

Water samples were collected from each segment of the local hydrology. Periodic samples of the irrigation water supply and the drainage waters were taken and analyzed to describe the net effect created by the plot studies. During the first year, field tailwater samples were taken to determine if manure materials were being carried from the field by surface runoff. These sampling efforts were discontinued when no detectable levels were found.

Water samples were also collected from flows passing below the 120 cm depth with a system of ten vacuum extractors schematically illustrated in Figure 7. In the fall of 1976 after the corn harvest, pits were excavated near the center of plots 3, 4, 5, 11, 21, 30, 31, 37, 38 and 39. The pits were excavated deep and wide enough to allow horizontal holes to be drilled into the insitu earth on one side. The soil taken from the holes was mixed with water to form a slurry which was subsequently used to refill the holes. The ceramic candles were then inserted into the holes and connected via a buried suction line to a central bank of air compressors. The vacuum

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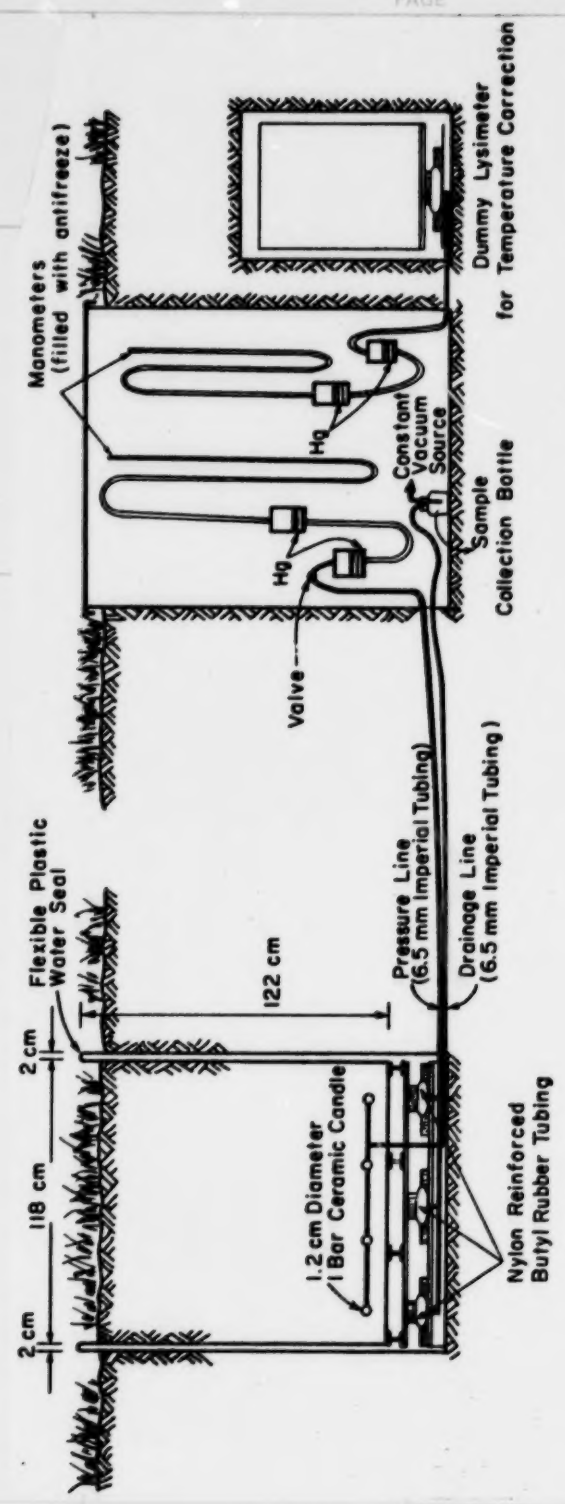
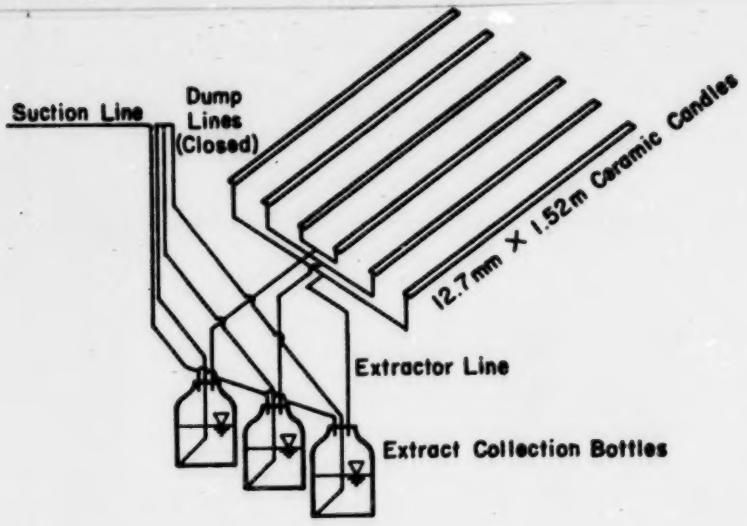
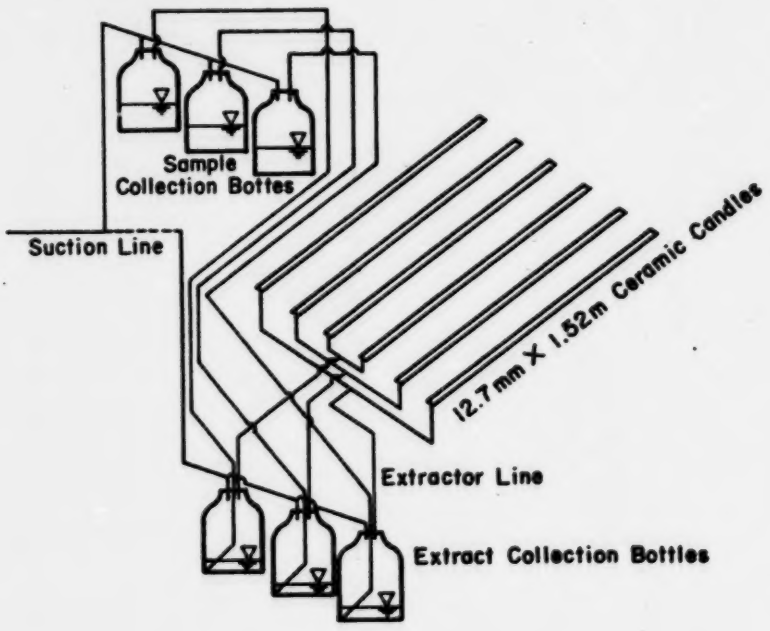


Figure 6. Schematic illustration of the lysimeter system used to measure potential evapotranspiration and the effects of soil moisture stress.



a) Vacuum Extractor System in the Operating Condition



b) Vacuum Extractor System in the Dumping Condition

Figure 7. Schematic diagram of vacuum extractor system.

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extractors worked generally well throughout the project and allowed a sampling of flows passing the bottom of the root zone. These samples were analyzed in the laboratory for salinity, NO_3-N, TOC, and NH_4-N.

In order to develop an estimate of the N balance in the plot systems, plant samples from each plot were taken at the time of harvest, air dried and evaluated for TKN. Only the plant parts above the soil surface were sampled. The N in plant parts within the soil were assumed to be measured with the soil sampling. During the 1978 season, corn samples were collected from several plots throughout the season to establish the time distributed N uptake rate. The uptake rates appeared to agree with published uptake curves.

LABORATORY ANALYSES

Sample Storage and Preparation

Soil, plant, and water samples were analyzed in the laboratory on the day of collection whenever possible. When immediate analysis was not possible, the soil and plant samples were frozen, and the water samples were refrigerated. The soil and plant samples were dried in an oven at 60° to 65°C and were ground to pass a 0.5 mm sieve in preparation for analysis.

Nitrogen

NO_3-N was analyzed using an Orion model 93-07 NO_3^- ion electrode. NO_3-N was extracted from the soil and plant samples with a 1:1 water extract. The procedure presented by Milham et al. (1970) was followed. NH_4-N was extracted from the soil and plant samples by a 2 molar (M) potassium chloride solution. NH_4-N was then determined using Orion model 95-10 NH_4^+ electrode. Samples were also analyzed for NO_3-N and NH_4-N by the magnesium oxide-Devarda alloy method described by Bremner (1965) during the first year of study. Results from the two methods were compared, and it was determined that the ion-specific electrodes provided accurate measurements and required much less time to complete.

TKN was determined by performing a semimicro-Kjeldahl digestion as described by Bremner (1965), making the digest alkaline by addition of 10 M sodium hydroxide and determining the amount of NH_4^+-N present by use of the Orion model 95-10 NH_4^+ electrode.

Carbon

Soil samples were analyzed for TOC carbon by the wet combustion method described by Allison (1965). The C content of the plant and water samples was not determined. Due to the complexity of this analysis, the laboratory personnel were unable to make a direct determination of the TOC content of each soil sample. Similarity of test procedures for COD suggested that TOC could be correlated with COD which was measured for all samples and therefore extended the TOC measurements to the entire data set. The measured TOC values from about 500 soil samples were related to the COD of the same soil samples. It was found that the TOC content was one-third of the COD value for the samples, and this factor was used to estimate TOC for the samples not tested.

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Salinity

A 1:1 soil water extract was prepared for determination of Cl^-, carbonate ($CO_3^=$), and bicarbonate (HCO_3^-) concentrations in the soil samples. These analyses were also performed on the water samples. Cl^- concentrations were determined by the mercuric nitrate-diphenylcarbazone method as described by the U.S. Environmental Protection Agency (1974). $CO_3^=$ and HCO_3^- were determined by means of a phenolphthalein titration and a mixed bromcresol green-methyl red titration as described by the American Public Health Association (1971). Periodic water and soil samples were also tested for Na^+, Ca^{++}, K^+, and sulfate ($SO_4^=$).

Analytical Quality Control

Care was taken to ensure the accuracy of the analyses performed in the field laboratory. Analytical grade reagents were used in all procedures and laboratory instruments were calibrated and checked frequently. Blank, duplicate, and spiked samples were included in each set of samples as they were analyzed. The blank would contain all of the reagents added to the samples and would be analyzed in the same manner of the constituent in question. Thus, any contamination due to impure reagents or dirty glassware would be detected. Duplicate samples were included to test the reproducibility of the procedure and the extent to which a representative portion of the sample had been selected for analysis. Known amounts of a standard containing the constituent being analyzed, or spikes, were also added to a replicate of one of the samples. This enabled the analyst to determine the accuracy of the procedure, for the two samples should differ only by the amount of the added standard. Thus, all of the likely sources of laboratory error were monitored on a day-to-day basis, and any errors were corrected before reporting results.

DESCRIPTION OF SIMULATION MODEL

It was originally planned to create three independent components of the model to better coordinate field data reduction and model performance tests. The first component was a simulation of surface irrigation uniformity developed for furrow irrigated conditions by Gerards (1978). Field evaluations during the first season showed that applied depths were consistently uniform over the plot under irrigating procedures set up at the project start. The furrows extending over three plots were relatively short given the furrow inflow rates used. Thus, the uniformity simulation was developed but was not used and will not be described here.

The second component of the modeling effort was the simulation of evapotranspiration rates from the plots. Because these processes represent the major water flux in the system, it was decided to model them independently in order to maximize the accuracy of the evaluations. The output of E_{to} simulations, including the K_{co} adjustment, were input as data to the third component, the simulation of subsurface water and chemistry.

During the course of this study, a comprehensive evaluation of existing models incorporating a N and water simulation was undertaken. Many of these models require input parameters which are generally unavailable for field

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conditions. In addition, the more detailed models require so much computational time that the expense involved would preclude their use for planning and management decision-making. It was concluded that the simulation model recently presented by Rao et al. (1980) provided the best state-of-the-art description of N behavior in the crop root zone of soils receiving animal manure. The input parameters required are readily available or may be easily estimated, and the model structure is simple enough to require minimal computer time and yet provide an adequate description of water and nitrogen dynamics in the crop root zone.

The model developed by Rao et al. (1980) contains various submodels which describe the processes related to manure and crop residue mineralization, soil N and C transformations, water and solute flow, and crop uptake of water and N. The individual simulations of crop-related processes were designed for corn, and are empirical in nature.

Evapotranspiration

E_{tp} was estimated with the Penman equation based on data collected at the weather station. The E_{tp} predictions were compared with the lysimeter data and the Penman equation was further calibrated.

The adjustment made by using the coefficient, K_{co}, is usually based on data given by Jensen (1969), Kincaid and Heermann (1974), and Doorenbos and Pruitt (1977). This coefficient is then multiplied by E_{tp} to yield the well-watered water use of the crop being grown, corn in this study. In the Grand Junction region, tests by Kruse et al. (1977) and Skogerboe et al. (1979a) showed these results to be generally applicable on a local scale.

Recent results from long-term lysimeter measurements at Kimberly, Idaho, have led to modified K_{co} values for arid, temperate inter-mountain climates (Wright, 1979). For computer applications, such as irrigation scheduling, it is convenient to express the maturity coefficient as a mathematical relationship. Using the methodology described by Doorenbos and Pruitt (1977), the growing season can be divided into four periods. Fitting this methodology to the recent results reported by Wright (1979) leads to the following mathematical format:

$$K_{co} = K_1;\ r \leq r_1 \tag{1}$$

$$K_{co} = K_1 + \left[\frac{r-r_1}{r_2-r_1}\right](K_2 - K_1);\ r_1 < r \leq r_2 \tag{2}$$

$$K_{co} = K_2;\ r_2 < r \leq r_3 \tag{3}$$

$$K_{co} = K_2 - \left[\frac{r-r_2}{r_4-r_3}\right] \cdot (K_2 - K_3);\ r_3 < r \leq r_4 \tag{4}$$

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where r is either: (a) the fraction of time which has elapsed from planting to effective cover; or (b) the number of days since effective cover. For field corn at the test site, the following numerical quantities were used: $K_1 = 0.16$; $K_2 = 0.98$; $K_3 = 0.15$; $r_1 = 0.56$; $r_2 = 1.0$; $r_3 = 50$; and $r_4 = 100$. In most situations, full cover conditions are achieved 70 to 80 days after planting with harvest following full cover by about the same interval.

Soil Water and Chemistry Simulation

The simulations of water in the region between the soil surface and the saturated zone above the water table is accomplished with the model reported by Rao et al. (1980) with modifications to the water uptake submodels to account for soil moisture stress (Kroeker, 1980). Data describing irrigation appliations are the basic input to the transport submodel while well-watered crop evapotranspiration is the basic input to the uptake submodel. If the irrigation uniformity model had been needed, its output would have replaced measured applications as input to the transport model.

Because the fate of the manure and its end products was of primary interest, a short review of the mathematical components of the N and C simulations will be given. Simulation of the N system in the unsaturated soil profile involved submodels of NO_3-N and NH_4-N transport, plant N uptake, C transformations, and N transformations.

Nitrogen Transport Submodel--

The N transport submodel calculates the movement of NH_4-N and NO_3-N due to mass transport of water. Neglecting flow due to molecular dispersion, the partial differential equation describing transient, one-dimensional solute transport may be written as:

$$\frac{\partial}{\partial t}(\theta C' + \rho S) = -\frac{\partial}{\partial x}(qC') \qquad (5)$$

where t is time, θ is volumetric soil-water content, ρ is soil bulk density, C' and S are, respectively, solution-phase and adsorbed-phase concentrations of the N species, x is vertical distance, and q is soil-water flux.

Assuming that the adsorption of NH_4-N is described by a linear and reversible isotherm, and the NH_4-N adsorption-desorption is an instantaneous process:

$$S = K_D C' \qquad (6)$$

where K_D is the distribution coefficient for ion-exchange. Substituting Equation 6 into Equation 5 yields:

$$\frac{\partial}{\partial t}[(\theta + \rho K_D) C'] = -\frac{\partial}{\partial x}[qC'] \qquad (7)$$

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Nitrogen Uptake Submodel--

Rao et al. (1980) devised empirical functions to describe N uptake consisting of both NO_3-N and NH_4-N. The maximum N uptake demand (Q_x) for corn under nonlimiting N or water supply was calculated using the experimental data of Watts and Hanks (1978):

$$FTNU = \begin{cases} 3.09937\ (FGS)^3; & 0 \leq FGS \leq 0.3 \\ -0.659\ FGS + 3.48\ (FGS)^2 - 0.929\ (FGS)^3 & \\ \quad -0.898\ (FGS)^4; & 0.3 \leq FGS \leq 1.0 \end{cases} \quad (8)$$

$$FTNU = CNU/TNU \quad (9)$$

$$FGS = t/TMAX \quad (10)$$

$$Q_x = \frac{d}{dt}\ (FTNU) \quad (11)$$

where FTNU is fractional total N uptake demand, FGS is fraction of growing season, CNU is cumulative uptake-N, TNU is total N uptake at crop harvest, t is time after planting, and TMAX is time from planting to harvest. Equation 8 represents a sigmoidal cumulative N uptake curve as shown in Figure 8.

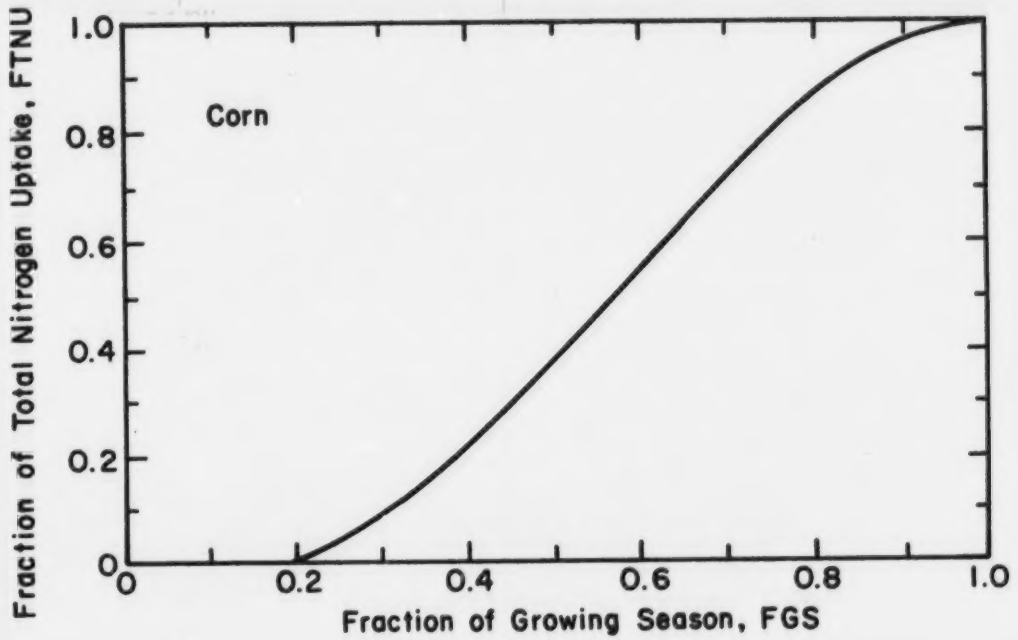

Figure 8. Fractional total N uptake (FTNU) plotted against fractional growth season (FGU) for corn. (After Rao et al., 1980).

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Carbon Transformation Submodel--

The C transformation submodel considers both the native soil Org-C and the Org-C resulting from the application of organic materials to the soil. The available C content in each depth increment is calculated for use in simulating denitrification losses in the N transformation submodel. A general diagram of this submodel is shown in Figure 9.

Stanford et al. (1975a) and Burford and Bremner (1975) have reported that denitrification rates were correlated with the amount of soil Org-C. Rao et al. (1980) assumed that the available fraction of the soil Org-C was represented by the water-extractable Org-C. The mathematical expressions used by Rao et al. (1980) were taken from the work of Burford and Bremner (1975) and Reddy et al. (1980). The water-extractable Org-C was separated into a readily-oxidizable portion (Fraction I) and a portion resistant to decomposition (Fraction II), as described by Reddy et al. (1979). The Fraction I Org-C was considered to be readily available, and was assumed to decompose in two phases in an attempt to represent two relative degrees of availability. The Fraction II Org-C was considered to decompose similarly to the native soil Org-C.

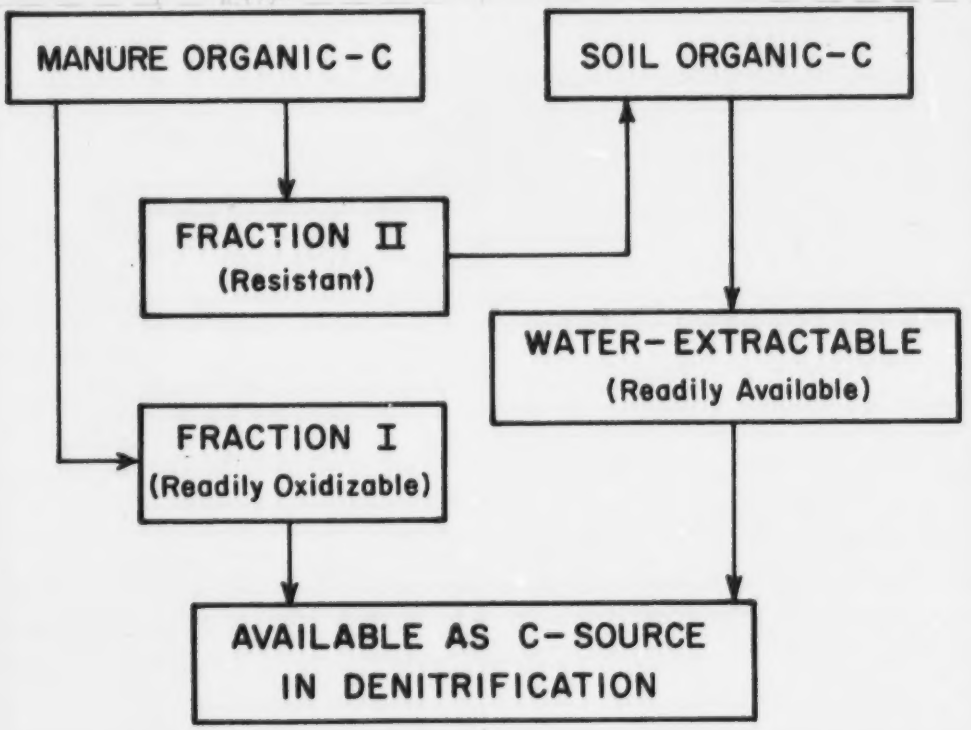

Figure 9. Partitioning of manure Org-C and soil Org-C in the C transformation submodel. (After Rao et al., 1980).

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The total amount of manure Org-C applied per gram (g) of soil (C_M) may be calculated given the manure loading rate, incorporation depth, and the manure Org-C content. Concentrations of readily oxidizable (C_{MAV}) and resistant (C_{MR}) manure Org-C are computed by:

$$C_{MAV} = (f_1 + f_2)\ C_M \tag{12}$$

$$C_{MR} = (1 - f_1 - f_2)\ C_M \tag{13}$$

where f_1 and f_2 represent the fractions of readily available Org-C in the two degradation phases. The changes in C_{MAV} values with time are calculated from:

$$-\frac{dC_{MAV}}{dt} = k_{ci}\ g_w\ C_{MAV} \tag{14}$$

where k_{ci} is the rate coefficient for available C consumption and the subscript i designates decomposition phase 1 or 2, g_w is an empirical weighting function to express the temperature dependence of k_{ci}, and

$$i = 1;\ f_1 + f_2 \geq (C_{MAV}/C°_{MAV}) \tag{15}$$

$$i = 2;\ f_1 + f_2 > (C_{MAV}/C°_{MAV}) \tag{16}$$

where $C°_{MAV}$ is the available manure Org-C concentration at t = 0. The C_{MAV} values calculated from Equation 14 are added to the water-extractable soil Org-C to obtain the total concentration of available C at time t. Values of f_1, f_2, k_{ci}, and other model parameters for various organic wastes may be obtained from Rao et al. (1980). Typical values for beef feedlot manure range from 0.22 to 0.37 for f_1, 0.06 to 0.15 for f_2, 0.0248 to 0.0459 day^{-1} for k_{c1} and 0.0048 and 0.0147 day^{-1} for k_{c2}.

Nitrogen Transformation Submodel--

As in the C transformation submodel, the native soil Org-N is considered separately from the manure Org-N. The soil N transformations are modeled as described by Davidson et al. (1978), and the model proposed by Reddy et al. (1979) is used to simulate the manure N transformations.

The manure Org-N is divided into different portions in the same way the manure Org-C was, as shown in Figure 10. The C:N ratio of the organic waste applied to the soil is assumed to determine whether net mineralization or net immobilization of N will occur. C:N ratios of less than 23 favor net mineralization and those greater than 23 favor net immobilization under aerobic soil conditions. Mineralization of manure N is considered to be the conversion of manure Org-N to NO_3-N.

The amount of the manure Org-N which will be either mineralized or immobilized upon application to the soil may be calculated by:

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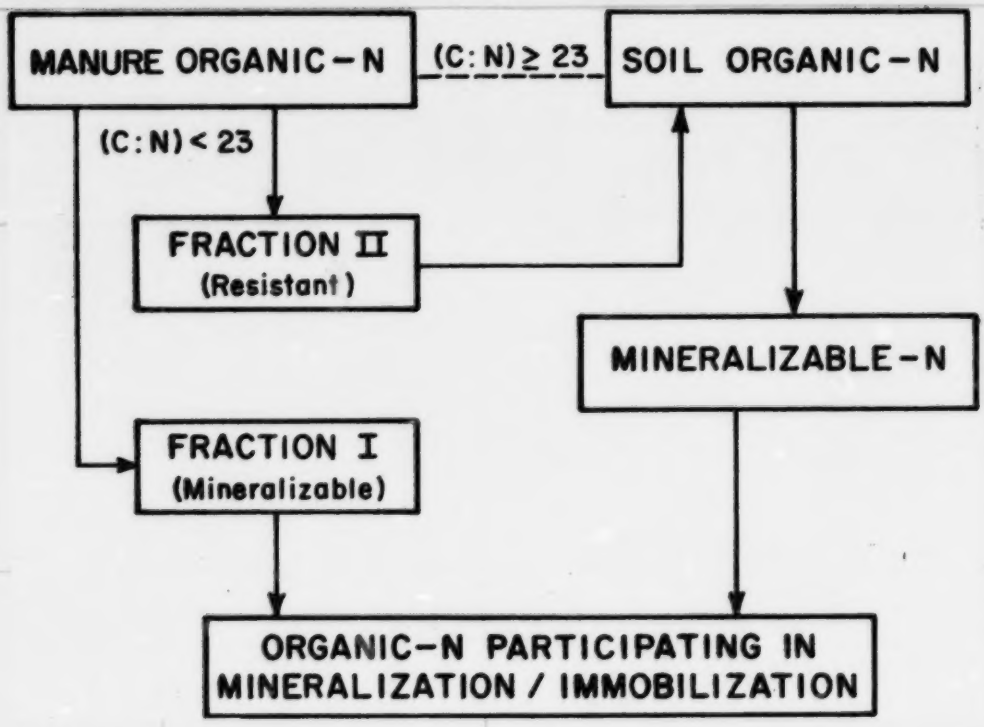

Figure 10. Partitioning of manure Org-N and soil Org-N in the N transformations submodel. (After Rao et al., 1980).

$$TX = TWN[1 - 0.043\ (C:N)_w] \tag{17}$$

where positive TX represents the amount of nitrogen potentially available for mineralization [microgram (μg)/cm^2 soil], negative TX represents the amount of N deficit for mineralization to occur (μg/cm^2 soil), TWN is total manure N (μg/cm^2 soil), and $(C:N)_w$ is the manure C:N ratio.

For soil applied organic materials with a C:N ratio less than 23, the amount of readily mineralizable nitrogen (N_x) at the time of application (t = 0) is:

$$N_x = \frac{TX}{(NMAN)(\Delta x)} \tag{18}$$

and

$$NMAN = \text{Integer}\left[\frac{COPDEP + 0.5\Delta x}{\Delta x}\right] \tag{19}$$

where COPDEP is the incorporation depth (cm). The amount (TWN-TX) is considered to be resistant, slowly mineralizable Org-N and is treated the same as the native soil Org-N. Based on the work of Stanford and Smith (1972) and

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Reddy et al. (1979), only 16.2 percent of the soil Org-N is considered to be readily mineralizable. Thus, the amount of resistant manure Org-N which is mineralizable (TS) is calculated as:

$$TS = 0.162\ (TWN - TX) \tag{20}$$

When organic wastes with C:N ratios greater than 23 are applied to the soil, the inorganic N is immobilized and then remineralized at a later time with the soil Org-N. Because of microbial metabolic activity, the C:N ratio will decrease with time and N will be released only after $(C:N)_w$ value is less than or equal to 23. The delay time (t_D) required for $(C:N)_w$ to decrease to the critical value of 23 is determined as:

$$t_D = \frac{[\ln (C/N)_w - \ln 23]}{k_m} \tag{21}$$

where k_m is the rate coefficient for organic material decomposition. Thus, for $(C:N)_w \geq 23$, all of the manure N is treated as soil Org-N after $t > t_D$.

The nitrogen transformation processes included in this submodel include: (1) nitrification of NH_4-N to NO_3-N; (2) mineralization of soil Org-N to NH_4-N; (3) mineralization of manure Org-N to NO_3-N; (4) immobilization of NH_4-N and NO_3-N to soil Org-N; and (5) denitrification of NO_3-N to N_2 and N_2O. These processes were assumed to follow first-order kinetics. Ion-exchange of NH_4^+ was simulated as an instantaneous process characterized by a linear and reversible isotherm. These processes are shown schematically in Figure 11.

The mathematical expressions describing these processes are:

$$\rho \frac{\partial}{\partial t} (N_s + N_m) = k_2 \theta C_3 + k_4 \theta C_4 - k_3 \rho (N_s + N_m) \tag{22}$$

$$\frac{\partial}{\partial t} (\rho S_4 + \theta C_4) = k_1 \theta C_4 - k_4 \theta C_4 + k_3\ \rho (N_s + N_m) \tag{23}$$

$$\theta \frac{\partial C_3}{\partial t} = k_1 \theta C_4 + k_m \rho N_x - k_2 \theta C_3 - \rho \frac{\partial G}{\partial t} \tag{24}$$

$$\rho \frac{\partial G}{\partial t} = k_5\ C_{AV} g_w \theta C_3 \tag{25}$$

$$\frac{\partial N_x}{\partial t} = -k_m N_x \tag{26}$$

$$S_4 = K_D C_4 \tag{27}$$

where: ρ = soil bulk density,
t = time
θ = volumetric soil-water content

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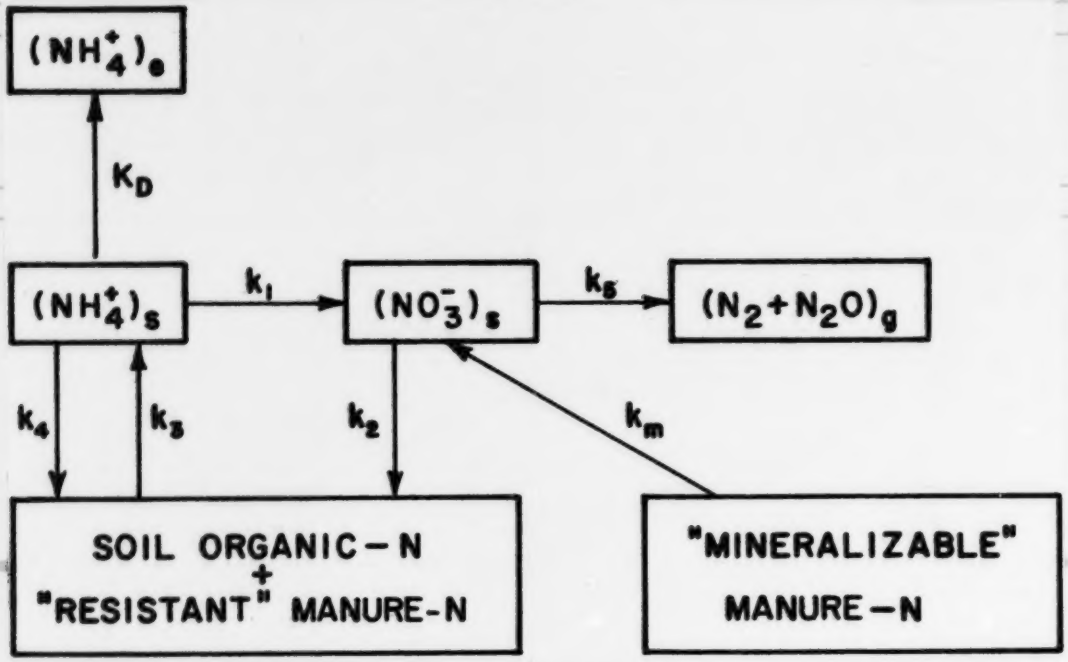

Figure 11. Schematic of the various processes considered in the nitrogen transformation submodel. (After Rao et al., 1980).

k_j = first-order rate coefficients; j = 1, 2, 3, 4, 5, and m (see Figure 11)

K_D = ion-exchange partition coefficient for NH_4+

N_s = mineralizable soil Org-N; N_s = 0.162 TON

N_m = resistant manure N

N_x = readily mineralizable manure N

TON = total soil Org-N

C_3 = NO_3-N solution concentration

C_4 = NH_4-N adsorbed-phase concentration

G = gaseous N (N_2 + N_2O)

C_{AV} = total available C

g_w = function describing the dependence of denitrification rate on soil-water content.

The above equations are applied to each soil depth increment. Davidson et al. (1978) and Rao et al. (1980) have presented summaries of published values for the rate coefficients used in Equations 22 to 26.

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SECTION 5

EVALUATION OF RESULTS

INTRODUCTION

The validity of a simulation model depends upon the degree to which the model can predict the actual behavior of the physical system it represents. In view of the simplifying assumptions that were required to develop the model and the temporal and spatial variability found in the field data collected, it would be astonishing if each of the processes being modeled were predicted with a high degree of accuracy. Since many of these processes were not measured in the field, the overall validity of the model must be deduced by comparing simulated and measured values of those parameters for which field data were collected. Thus, a comparison of predicted and measured NO_3-N, Org-N, and soil-water profiles will be presented. The NO_3-N concentration in the extractors will also be compared with the predicted NO_3-N concentration at the 120 cm depth. The computed mass of N uptake by the corn plants and the computed mass of Org-C in the root zone will be compared to the amounts measured in the field. Finally, the performance of the evapotranspiration submodel will be discussed.

SOIL NITROGEN

The movement of NO_3-N into a groundwater supply is a significant water quality hazard associated with application of animal manure to irrigated cropland. Therefore, it was decided to attempt to adjust the N transformation rate coefficients so that the predicted NO_3-N profiles corresponded as closely as possible to the NO_3-N profiles which were measureed at the end of each growing season. A group of plots which spanned the entire range of manure treatments and irrigation regimes were chosen for this process, and a single value for each rate constant was determined to produce the "best-fit" for the group of plots as a whole. The model was then applied to the remaining plots where it was determined that the selected rate coefficients did indeed provide an adequate description of the NO_3-N distribution with depth in the soil profile.

The selected rate constants are shown in Table 2. The adsorption partition coefficient (K_D) was estimated as 0.2 ml/g. The values selected for K_D, the nitrification (k_1), immobilization (k_2 and k_4), and denitrification (k_5) rate coefficients are essentially those presented by Rao et al. (1980). The value selected for the mineralization rate constant of soil Org-N, k_3, is considerably smaller than the rate constants reported by Stanford and Smith (1972) for surface soils.

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TABLE 2. NITROGEN TRANSFORMATION RATE CONSTANTS

Process	Symbol	Rate Constant
$NH_4^+ \rightarrow NO_3^-$	k_1	0.036 day^{-1}
$NO_3^- \rightarrow$ Org-N	k_2	0.0039 day^{-1}
Org-N $\rightarrow NH_4^+$	k_3	0.000024 day^{-1}
$NH_4^+ \rightarrow$ Org-N	k_4	0.0078 day^{-1}
$NO_3^- \rightarrow N_2 + N_2O$	k_5	0.0001 $(hr\ ug/g)^{-1}$
Manure N $\rightarrow NO_3^-$	k_m	0.0016 day^{-1}

However, it agrees favorably with the value reported by Tanji et al. (1979) as an average rate constant for the entire soil profile. A value 0.0016 day^{-1} for manure mineralization (k_m) results in the mineralization of about 60 percent of the applied manure N in a growing season, which agrees with results reported by McCalla et al. (1970).

Nitrate Profiles

A comparison between the measured and predicted NO_3-N profiles for plot 3 for all three years of the study is shown in Figure 12. Plot 3 was irrigated with an allowable soil moisture depletion (ASMD) of 0.6 and an IRF of 0.75. Manure was applied each year. The manure was incorporated into the soil to a depth of 20 cm by disking immediately after application. The high NO_3-N concentration in the top 20 cm of soil is predicted reasonably well, except for the first year.

The type of discrepancy between measured and predicted NO_3-N profiles apparent in the 1977 graph in Figure 12 occurred occasionally in various plots and warrants further discussion. The ability to correctly predict the concentration of any soluble species with depth is very much dependent upon the accurate prediction of soil-water movement. In this case, it is likely that the water transport submodel underpredicted the volume of water which was leached below the root zone. Consequently, the N transport submodel erroneously predicted a buildup of NO_3-N in the lower root zone. The fact that each of the individual submodels are interrelated, and that errors in calculations made by one submodel may either be magnified or compensated for by the other submodels, should be kept in mind as model output is examined for its validity.

Shown in Figure 13 are the NO_3-N profiles at the end of each season for plot 36, a plot irrigated at the ASMD = 0.3 level with an IRF = 1 value. This plot only received a low manure treatment at the start of the study. The model slightly underpredicted the NO_3-N levels in the upper 20 cm, but simulated the lower profile extremely well.

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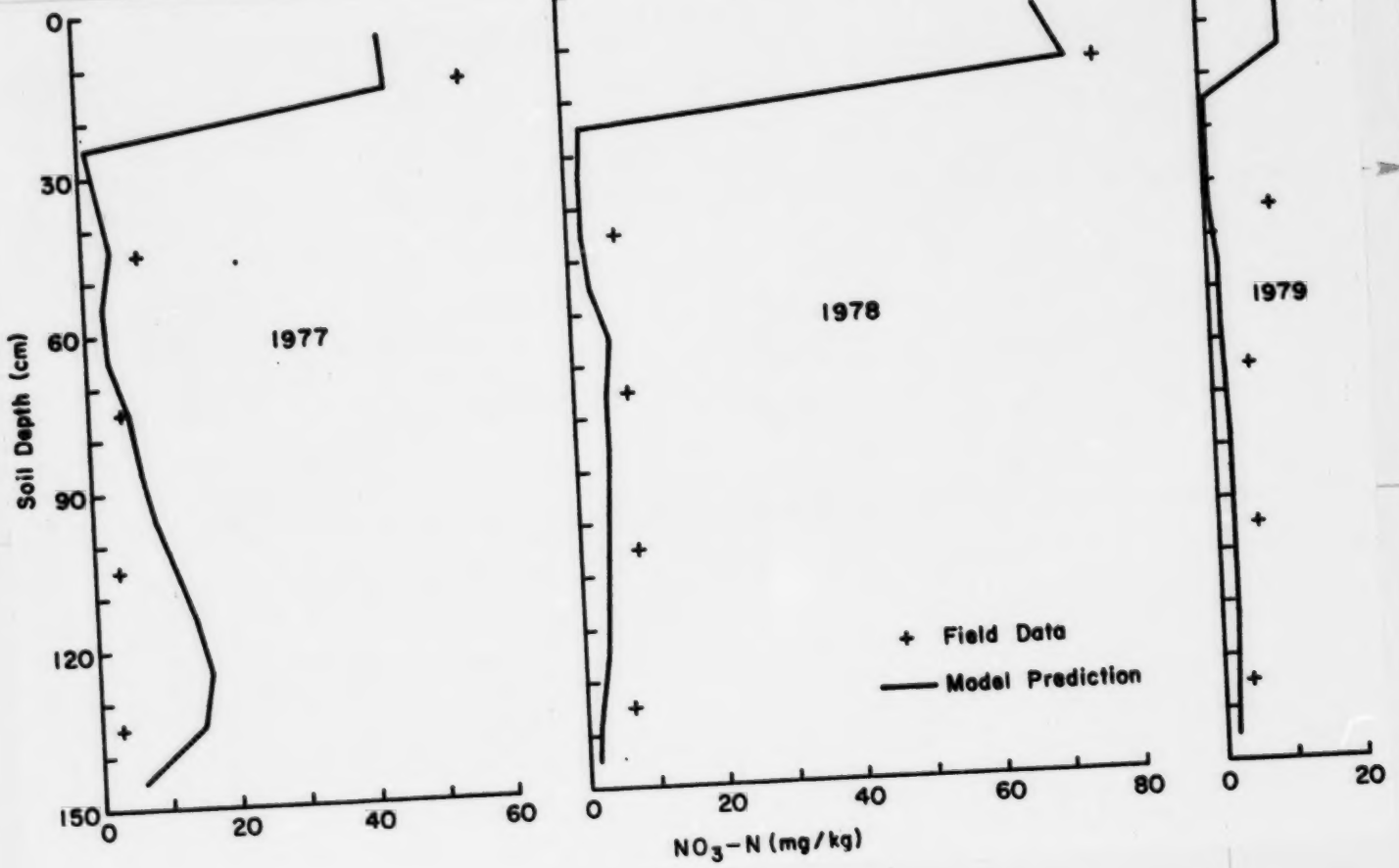

Figure 12. Comparison of measured and predicted NO_3-N profiles for Plot 3.

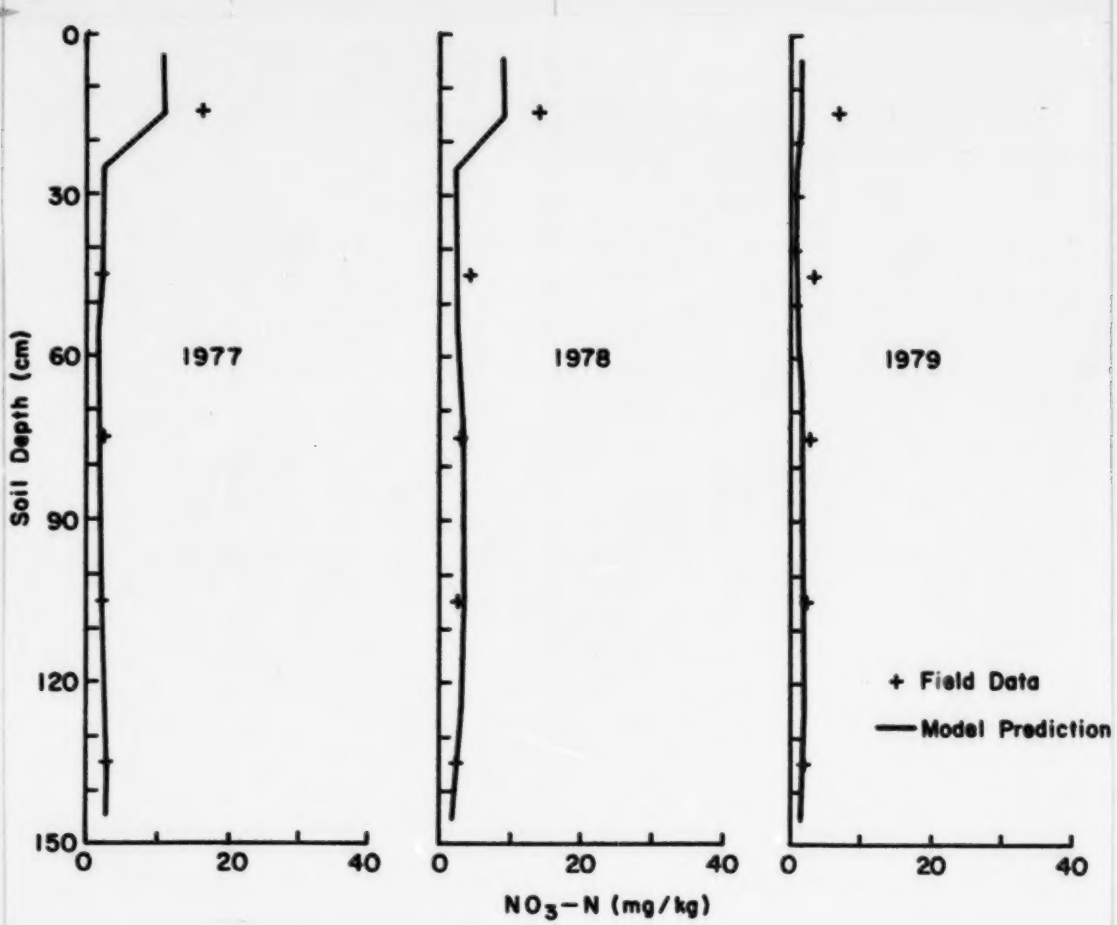

Figure 13. Comparison of measured and predicted NO_3-N profiles for Plot 36.

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The NO_3-N profiles at the end of the first and last years for plot 30, which received no manure, are shown in Figure 14. This plot received the normal irrigation treatment (ASMD = 0.6) with an IRF = 0.75. Again, the model underpredicted the NO_3-N levels in the top 60 cm of the profile but simulated very accurately the concentrations found in the lower root zone. The fact that the NO_3-N concentrations for this control plot are simulated accurately would tend to indicate that the rate coefficients selected are suitable for describing the N transformations.

The comparisons between measured and predicted NO_3-N profiles shown in Figures 15 to 19 are included to display typical results for plots receiving a further variety of the treatments which were investigated. Plot 21 received ASMD = 0.3 irrigations at IRF = 0.5 and a high manure loading at the beginning of the 1977 season. Plot 53 was irrigated daily (ASMD = 0.15) at an IRF = 0.75 value and received medium manure loadings at the beginning of the 1977 and 1978 seasons. The error evident in the 1978 profile for plot 53 is most likely due to underpredicting the amount of water (and thus NO_3-N) which was leached from the root zone. Plot 19 was irrigated at an ASMD = 0.6 frequency and IRF = 0.5 and received a low manure loading at the beginning of 1977. Plot 41 received ASMD = 0.3 irrigations with IRF = 0.75 and a high manure loading at the start of the 1977 season. Plot 44 was irrigated daily at IRF = 1 and received a medium manure loading, also at the start of the 1977 season.

A comparison between the simulated seasonal NO_3-N solution concentration at the 120 cm depth and the measured concentrations from two extractors is shown in Figure 20. It is seen that the model correctly predicted the timing of the peak concentration levels and simulated the NO_3-N nitrate concentration at the bottom of the root zone reasonably well throughout the entire season.

The model appears to provide an adequate description of the NO_3-N concentrations with depth for the entire range of conditions investigated. Large discrepancies between measured and predicted values did exist for approximately 20 percent of the plots in the study, but these discrepancies did not seem to be correlated with the type of treatment the plot had received. It is difficult to determine conclusively whether these errors were due to inadequacies in the model or in the measured data. However, in view of the large areas of the plots involved and the limited amount of sampling, it is safe to conclude that the data collected in the field was not always representative of the actual amounts of the N species present.

A graphic representation of the magnitude of the errors is shown in Figures 21 and 22, where the 45 degree line represents the ideal case when measured values equal predicted values. Figure 21 shows that the model consistently underestimated the total mass of NO_3-N in the entire root zone. The average absolute deviation ($\bar{d}_A$) was computed by:

$$\bar{d}_A = \frac{\sum_{i=1}^{n} |X_{i,\,pred} - X_{i,\,meas}|}{n} \qquad (28)$$

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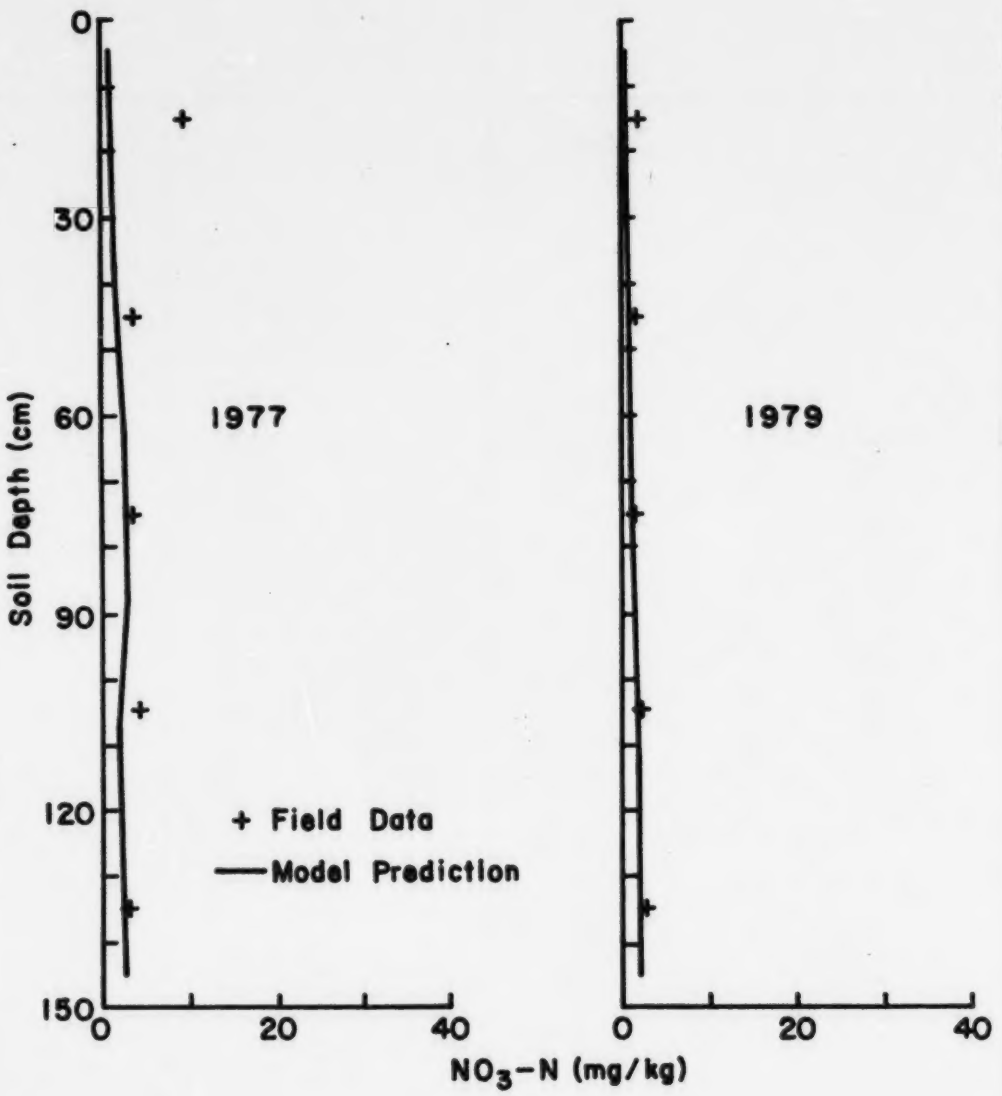

Figure 14. Comparison of measured and predicted NO_3-N profiles for Plot 30.

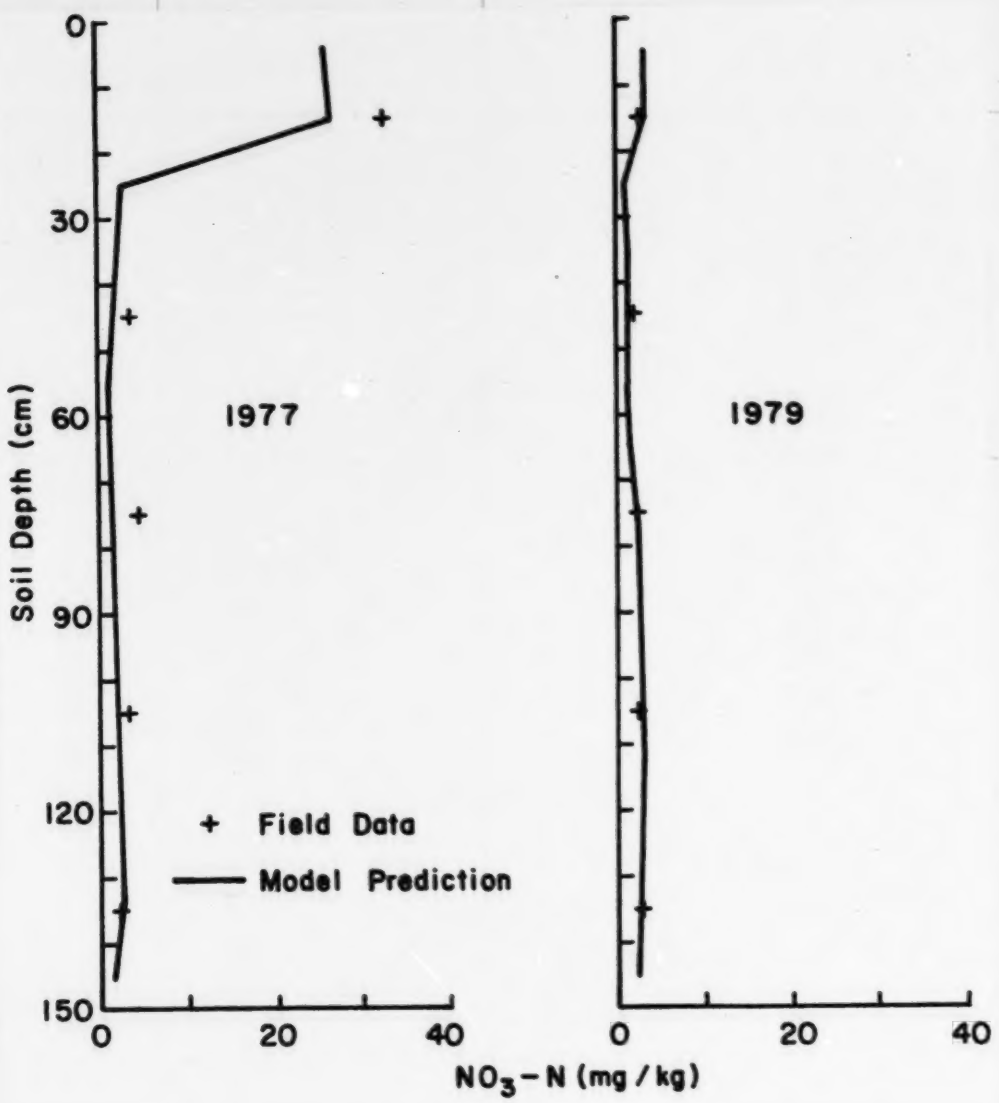

Figure 15. Comparison of measured and predicted NO_3-N profiles for Plot 21.

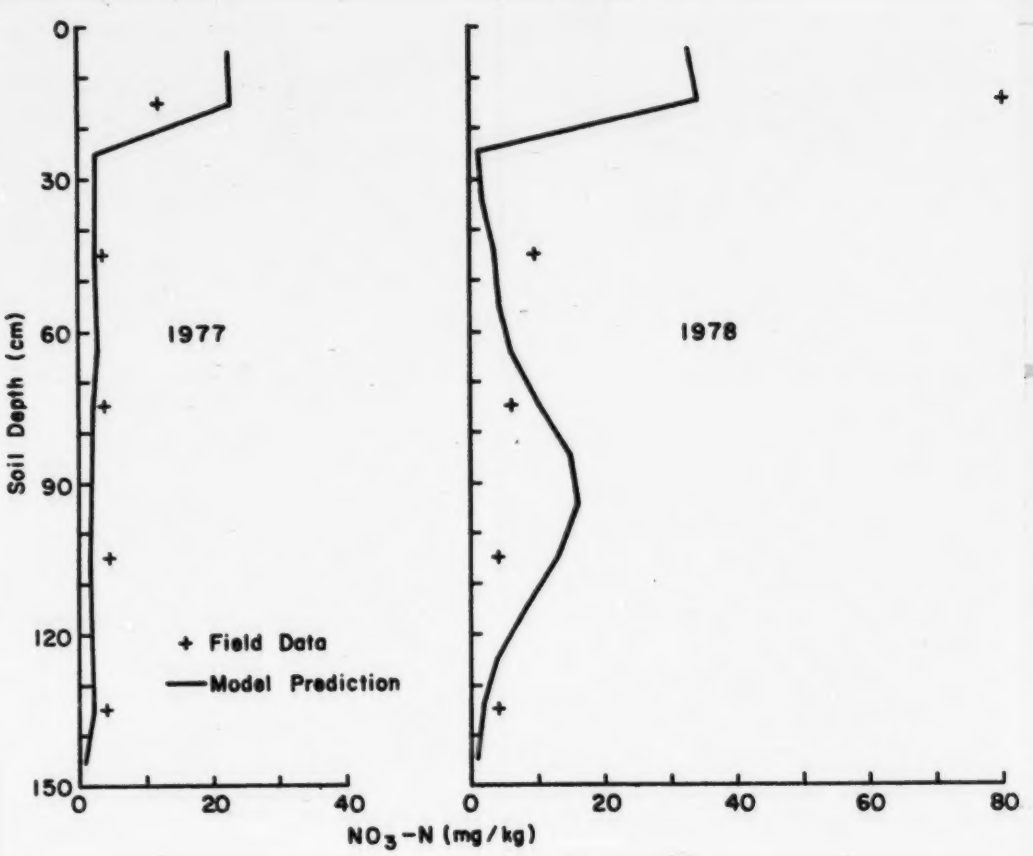

Figure 16. Comparison of measured and predicted NO_3-N profiles for Plot 53.

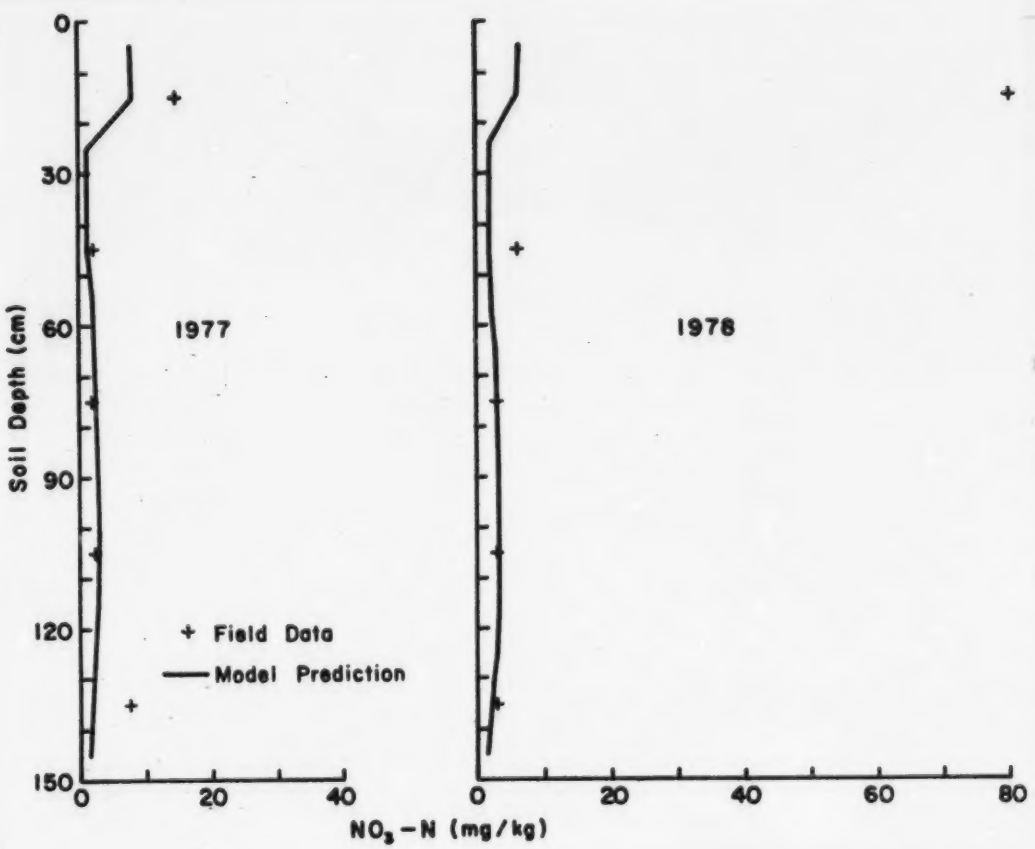

Figure 17. Comparison of measured and predicted NO_3-N profiles for Plot 19.

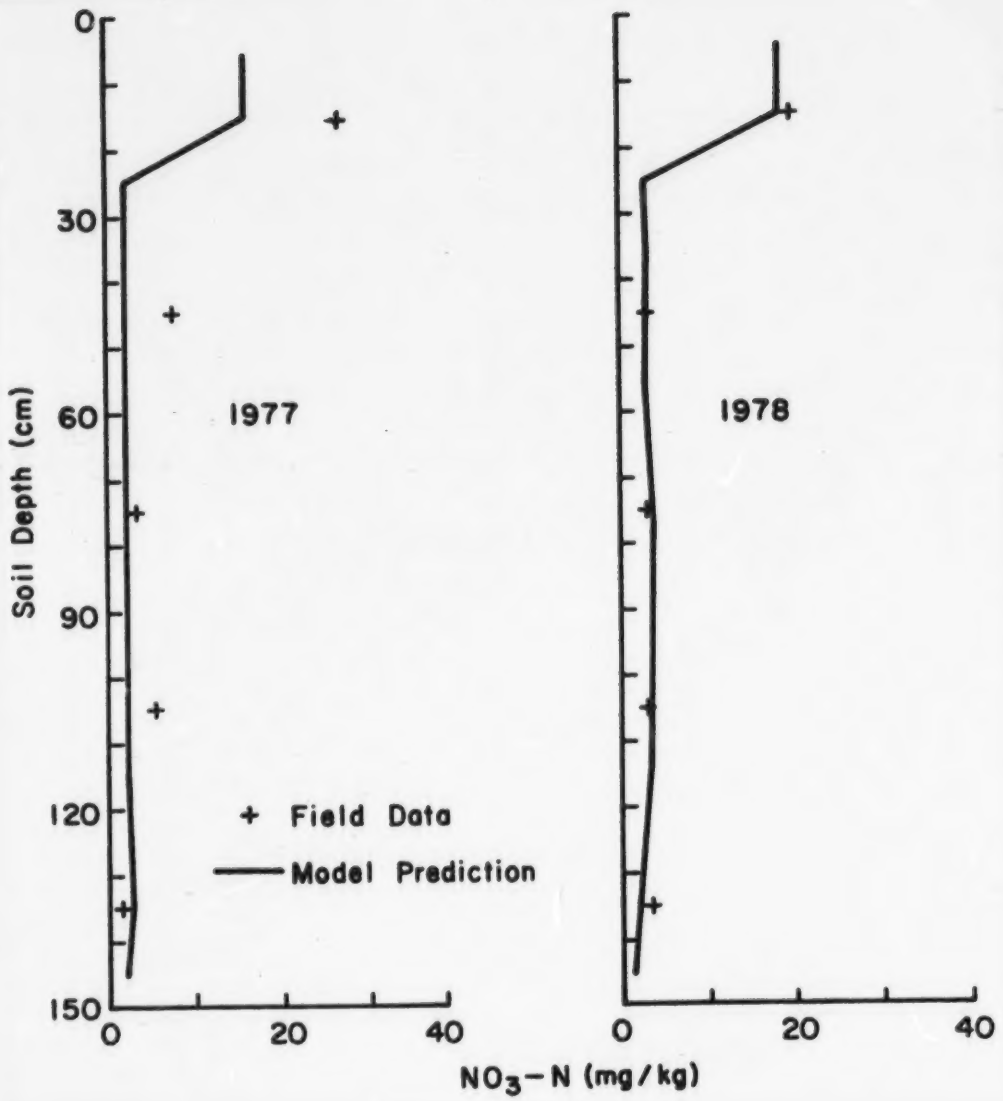

Figure 18. Comparison of measured and predicted NO_3-N profiles for Plot 41.

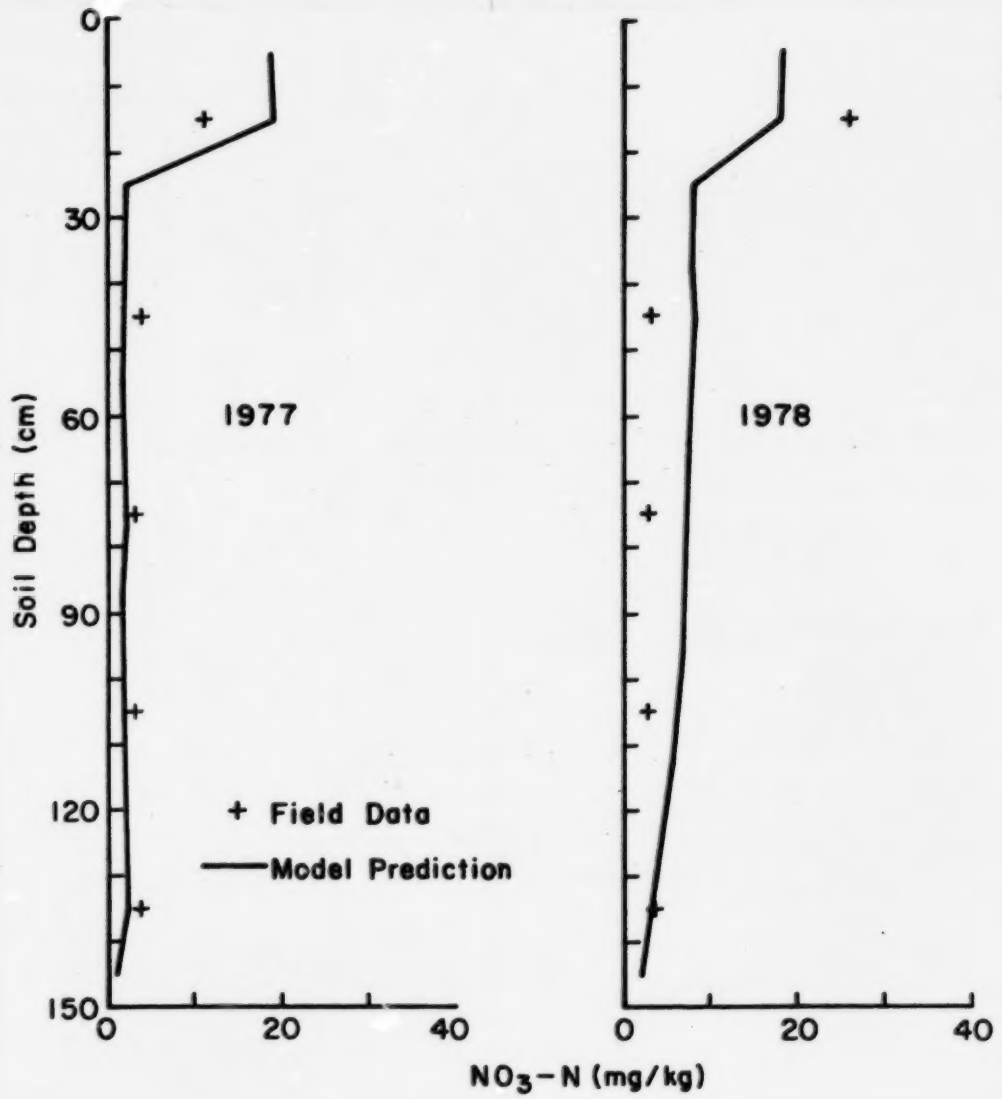

Figure 19. Comparison of measured and predicted NO_3-N profiles for Plot 44.

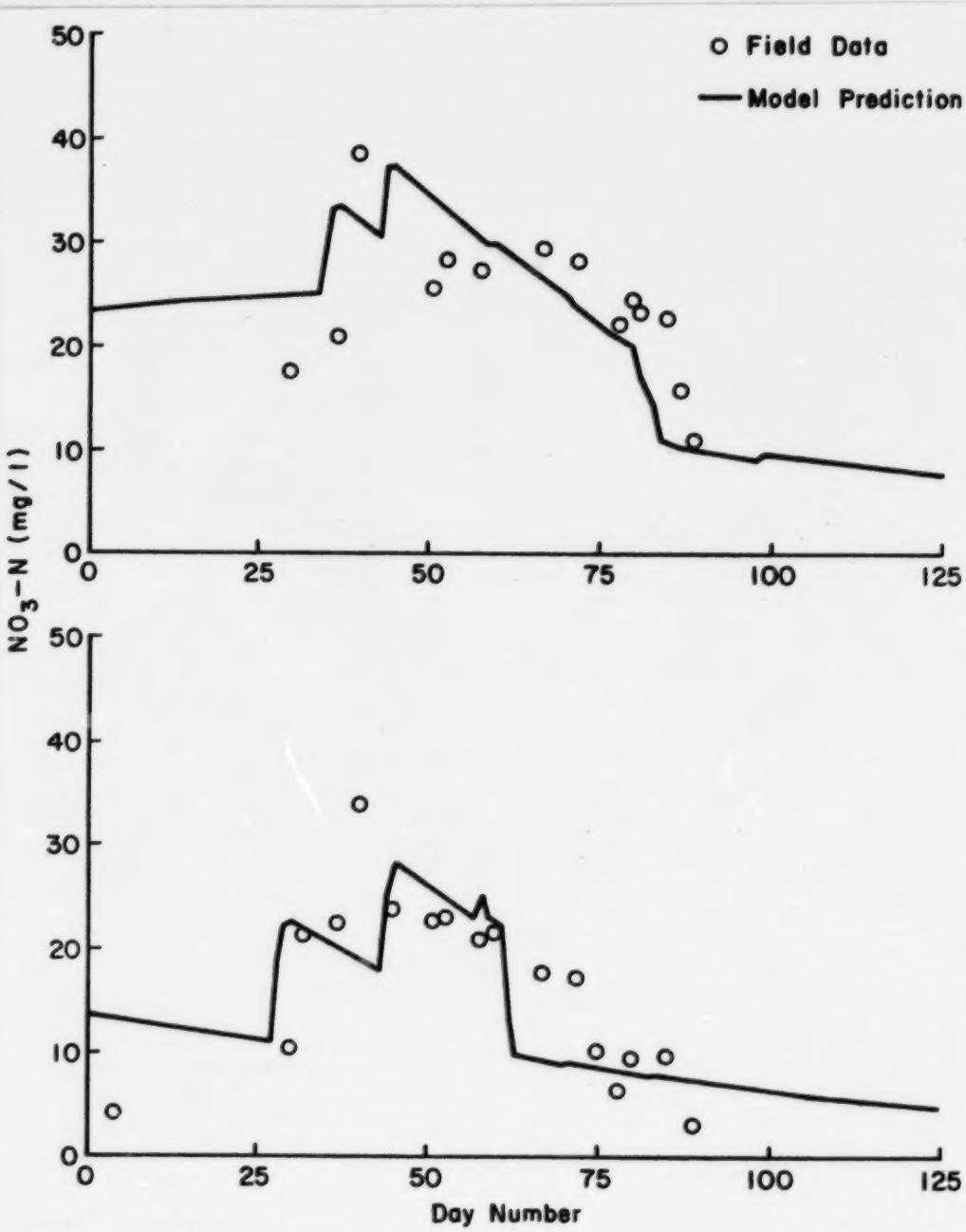

Figure 20. Comparison of measured and predicted NO_3-N concentration at the 120 cm depth.

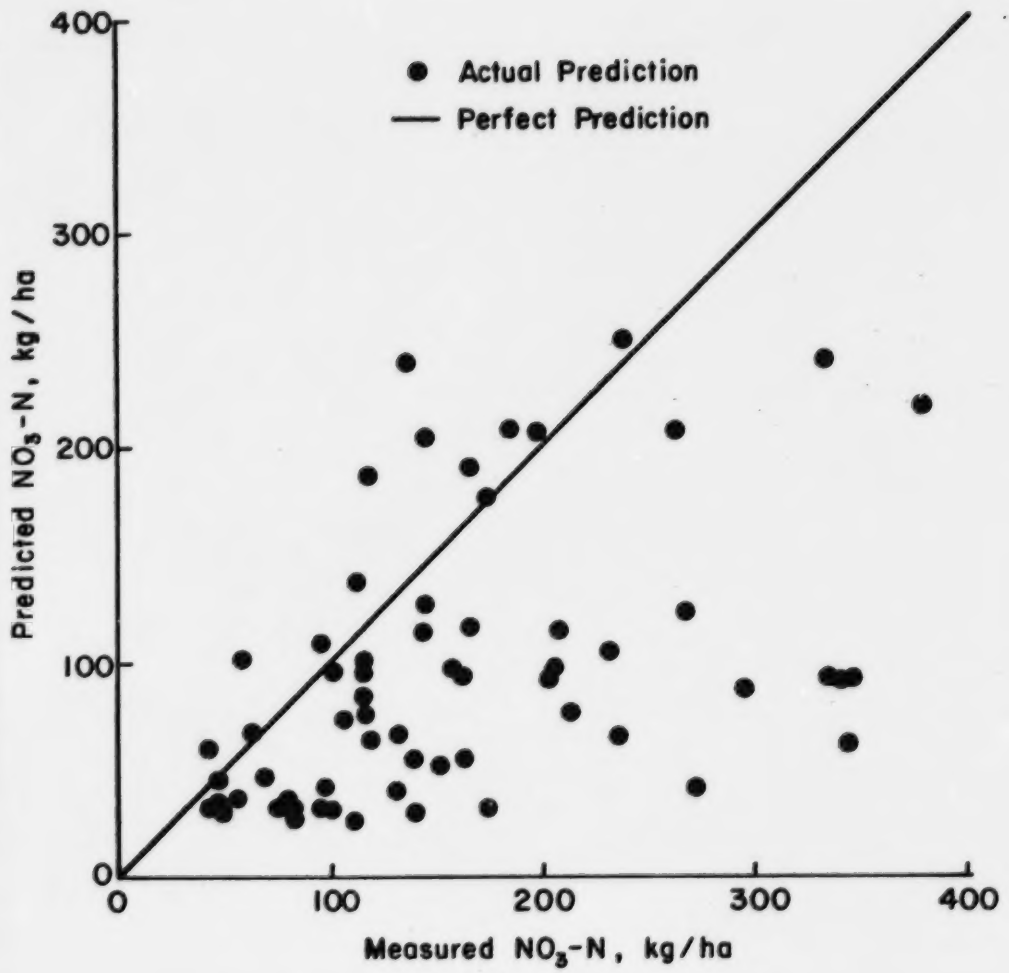

Figure 21. Comparison of measured and predicted amounts of NO_3-N in the entire root zone.

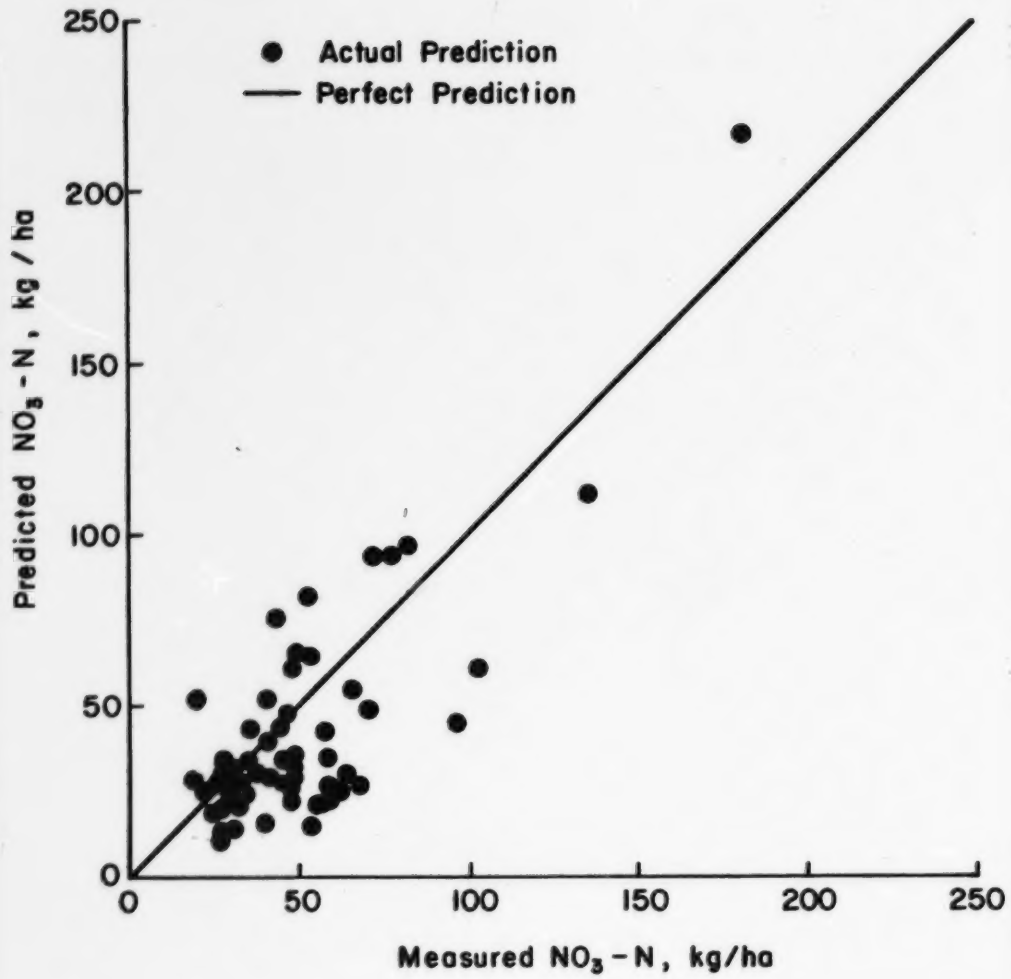

Figure 22. Comparison of measured and predicted amounts of NO_3-N in the portion of the root zone between 60 and 150 cm.

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where $X_{i,pred}$ is the value predicted by the model, $X_{i,meas}$ is the value measured in the field, and n is the number of samples. The average absolute deviation for the total mass of NO_3-N in the root zone was 78 kg/ha. Most of this error is due to the failure of the model to predict the large concentrations measured in the upper 60 cm of soil. When only the portion of the root zone below 60 cm is considered, the amount of error in predicting the mass of NO_3-N present in the soil is reduced considerably, as shown in Figure 22. The average absolute deviation for the mass of NO_3-N in the lower 90 cm of the root zone is 15 kg/ha.

There are two likely explanations for the difficulty in modeling the NO_3-N levels in the upper 60 cm. McLaren (1970) suggested that the magnitude of the kinetic rate coefficients are dependent upon the size of the microbial population responsible for each transformation. The population of microbial organisms is, in turn, dependent upon the energy source available at any given depth in the soil profile. For this reason, Davidson et al. (1978) assumed that the magnitude of the rate coefficients will decrease exponentially with depth in a similar fashion to the organic matter distribution in the soil profile. The same assumption was made in the model of Rao et al. (1980), which was used in this study, even though the latter model considers the application of manure materials. Therefore, the rate coefficients supplied for the model were assumed to apply for the surface depth increment and were decreased at each subsequent depth increment in proportion to the corresponding decrease in the organic-N content.

In many soils the Org-N content decreases considerably between the surface and the bottom of the root zone. The Org-N distribution in the soil found at the field location used in this study, however, was more or less constant with depth. Thus, the rate coefficients supplied for the surface tended to be only slightly larger than those calculated for the lower portions of the soil profile, even though there was an additional energy source available in the surface 20 to 30 cm due to the application of animal manures. The model assumed that the rate coefficients for mineralization of the soil organic matter were unaffected by the addition of manure. The manure increased the population of microorganisms and probably also affected the rates at which soil organic matter was mineralized. The consideration of the manure contribution to the available energy source, and the subsequent adjustment of the soil Org-N mineralization rate constant (k_m), would most likely result in more accurate prediction of the nitrate levels in the upper depth increments.

The second possible explanation for the underprediction of NO_3-N in the upper 60 cm involves the method of collecting the surface soil samples. The sample collected for the 0 to 30 cm layer consisted of a composite of the 20 cm soil core sample from the layer, and six grab samples collected with a shovel near the surface. It is likely that these grab samples often contained soil and manure materials exclusively from the 0 to 15 cm layer, resulting in a composite sample which was more representative of the higher NO_3-N levels found in the 0 to 15 cm layer than the average NO_3-N level for the entire 0 to 30 cm layer.

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Organic Nitrogen Profiles

Rao et al. (1980) assume that the soil Org-N content decreases exponentially with depth. Therefore, the Org-N content is described by:

$$\text{Org-N} = \text{ORGO} * \exp(\text{OR}*x) \qquad (29)$$

where x is soil depth, ORGO is the soil Org-N content at x = 0, and OR is an empirical coefficient describing the rate of decrease of soil Org-N with soil depth. Given values ORGO and OR, the model calculates the intial Org-N distribution at the beginning of each season according to Equation 29. The changes in Org-N content throughout the season are then computed by the equations contained in the N submodel.

Separate OR values for each plot were obtained by averaging the data collected at each depth for each plot, and fitting an exponential curve through these average values. Values of ORGO were obtained by forcing the measured and predicted Org-N contents at 75 cm to be equal for each preseason sampling, that is:

$$\text{ORGO} = \frac{\text{Org-N}(75)}{\exp(\text{OR}*75)} \qquad (30)$$

End of season comparisons between measured and predicted Org-N profiles for a range of treatments are shown in Figures 23 and 24. The treatments each plot received are summarized in Table 3. The irrigation treatments are described in Table 3 by the letter N, H, or D, representing ASMD = 0.6, 0.3, and 0.15, respectively, followed by the number 0.5, 0.75, or 1.0, which represents E_a or IRF of the specified irrigation. The manure loading rate for each year of the study is described by the letter H, M, L, or O, representing high, medium, low or zero loading rates, respectively.

TABLE 3. EXPERIMENTAL TREATMENTS RECEIVED BY THE PLOTS SHOWN IN FIGURES 23 AND 24

Plot	Irrigation treatment	Manure loading rate
19	N/0.50	L-0-0
30	N/0.75	0-0-0
12	N/1.00	H-0-L
21	H/0.50	H-0-0
36	H/1.00	L-0-0
50	H/0.75	M-0-0
4	D/0.75	H-0-M
5	D/0.50	H-0-M

Since the changes in soil Org-N due to transformations during a growing season are small compared to the total amount of Org-N present in the soil profile, the model is much more sensitive to the initial computed Org-N

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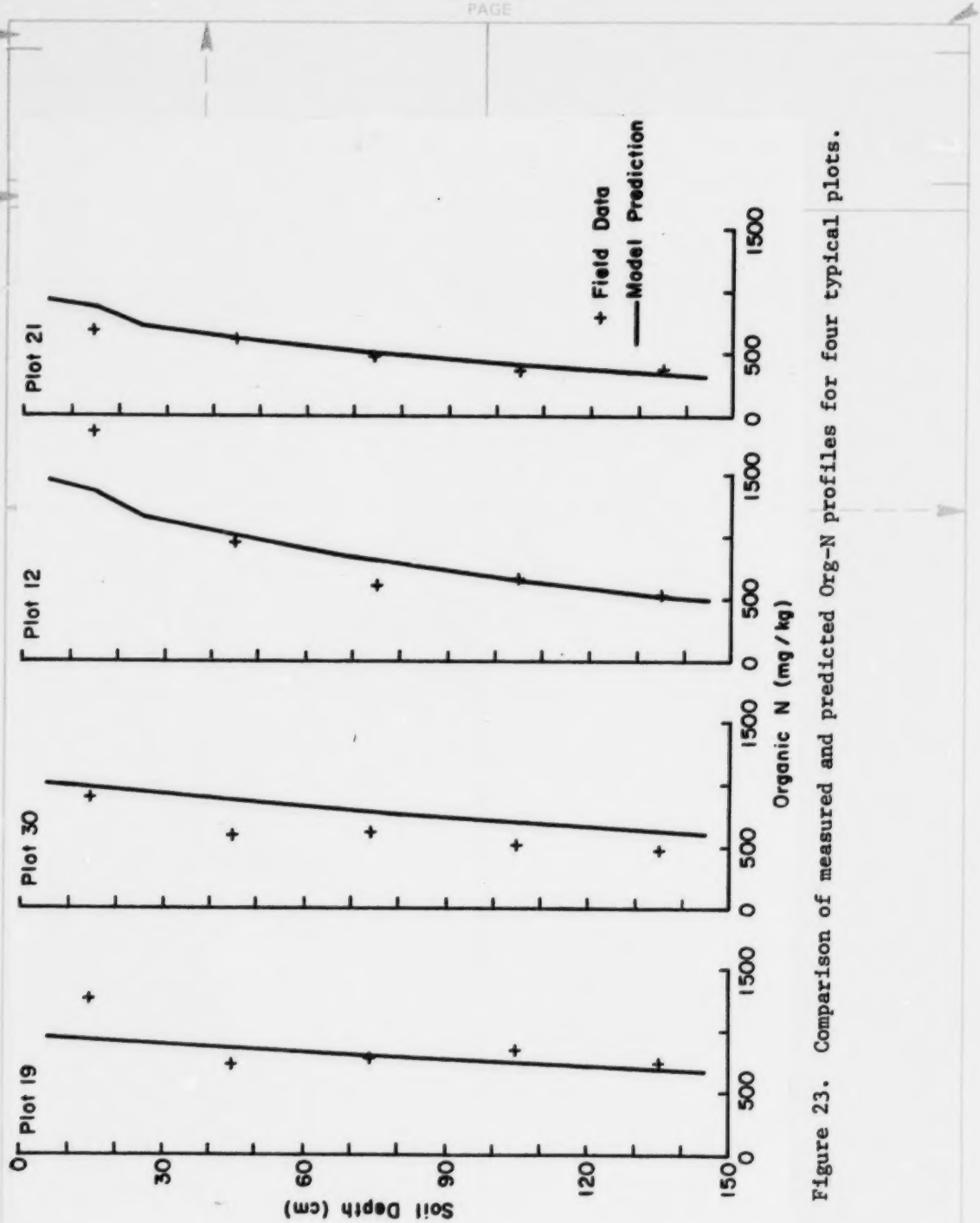

Figure 23. Comparison of measured and predicted Org-N profiles for four typical plots.

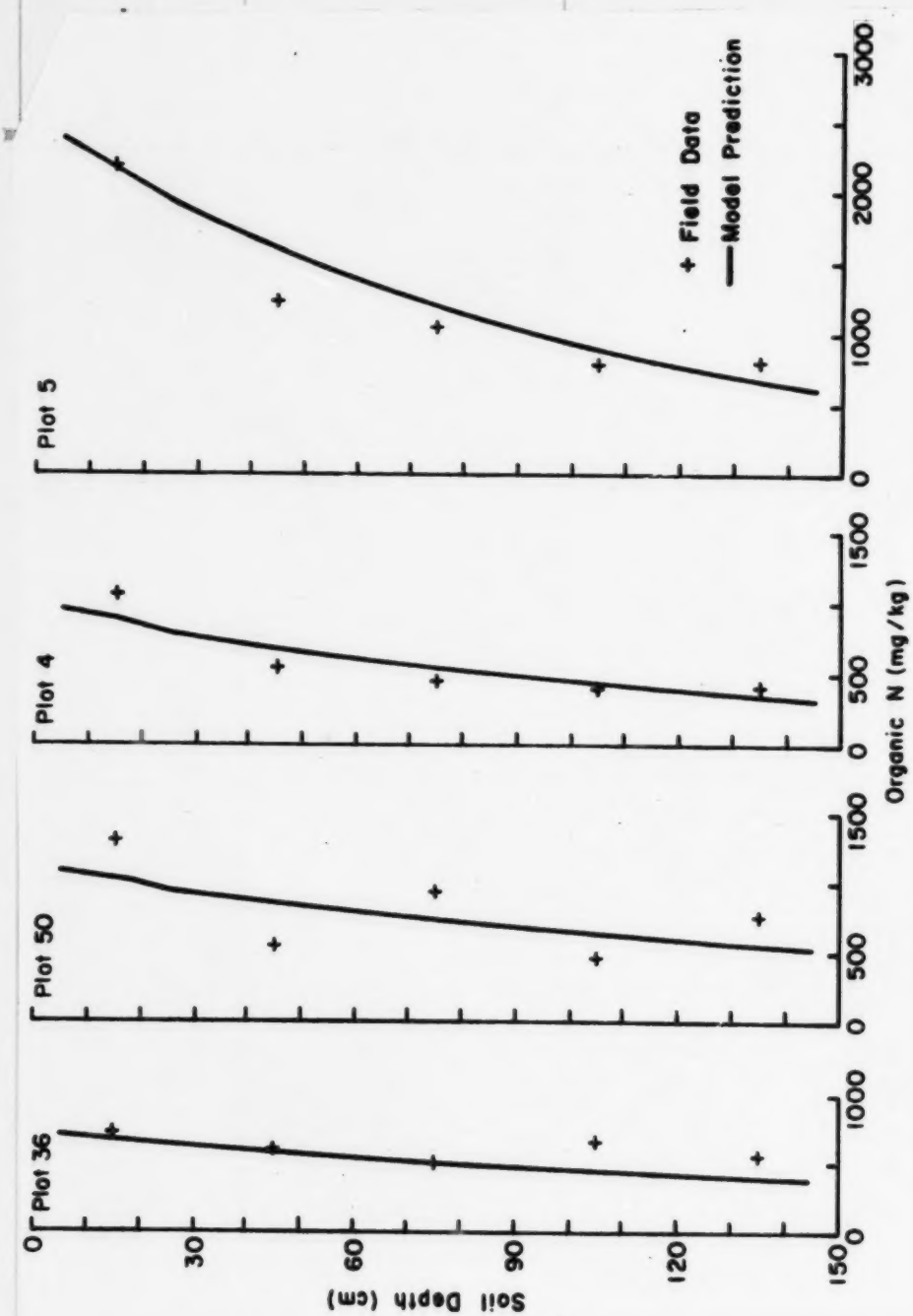

Figure 24. Comparison of measured and predicted Org-N profiles for four typical plots.

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distribution (i.e., the OR and ORGO values) than to the N transformation rate coefficients. Thus, the errors involved in predicting the total mass of Org-N present in the root zone are due mainly to natural variability in Org-N content often found in the preseason and post-season soil samples. The errors in predicting the mass of Org-N in the 120 cm root zone are shown in Figure 25. The average absolute deviation was found to be 4,700 kg/ha.

SOIL WATER

The water submodel input parameters used in the simulation were a depth increment of 10 cm, an infiltration rate of 1 cm/hr, a field capacity moisture content of 0.4 cm^3/cm^3, a wilting point moisture content of 0.2 cm^3/cm^3, a redistribution period of three days, and a bulk density of 1.45 gm/cm^3 at the surface and 1.55 gm/cm^3 below 30 cm. The water submodel was found to be most sensitive to the field capacity moisture contents, θ_{fc}, so these were estimated for each plot from the soil moisture data collected after irrigation events. It was found that the water model could be "fine-tuned" to predict the soil water distribution very accurately by varying the θ_{fc} values with each depth increment. Since values of θ_{fc} as a function of depth are rarely available and difficult to estimate for field conditions, it was decided to evaluate the model assuming θ_{fc} to be a constant.

Three typical end-of-season soil water profiles are shown in Figure 26. The irrigation treatments these plots received are displayed in Table 4. It is evident from examination of Figure 26 that the model quite effectively

TABLE 4. IRRIGATION TREATMENTS FOR THE PLOTS SHOWN IN FIGURE 26

Plot	IRF	θ_{fc} (cm^3/cm^3)
28	1.00	0.35
37	0.75	0.37
2	0.50	0.37

simulates the soil moisture distribution in the root zone. The overprediction of soil moisture content in the upper 30 cm seen in the profiles of plots 2 and 28 was typical of many of the experimental plots. This discrepancy is most likely due to either water uptake by the many weeds which were present in the field or by the uptake distribution being more sigmoided rather than the linear distribution used in the model.

A comparison between the measured and predicted total amounts of water present in the root zone at the end of each season is shown in Figure 27. The average absolute deviation was 4.1 cm of water. The average amount of water in the soil profile at the end of the season was 37.2 cm, which amounts to an average absolute error of 11 percent in the model predictions.

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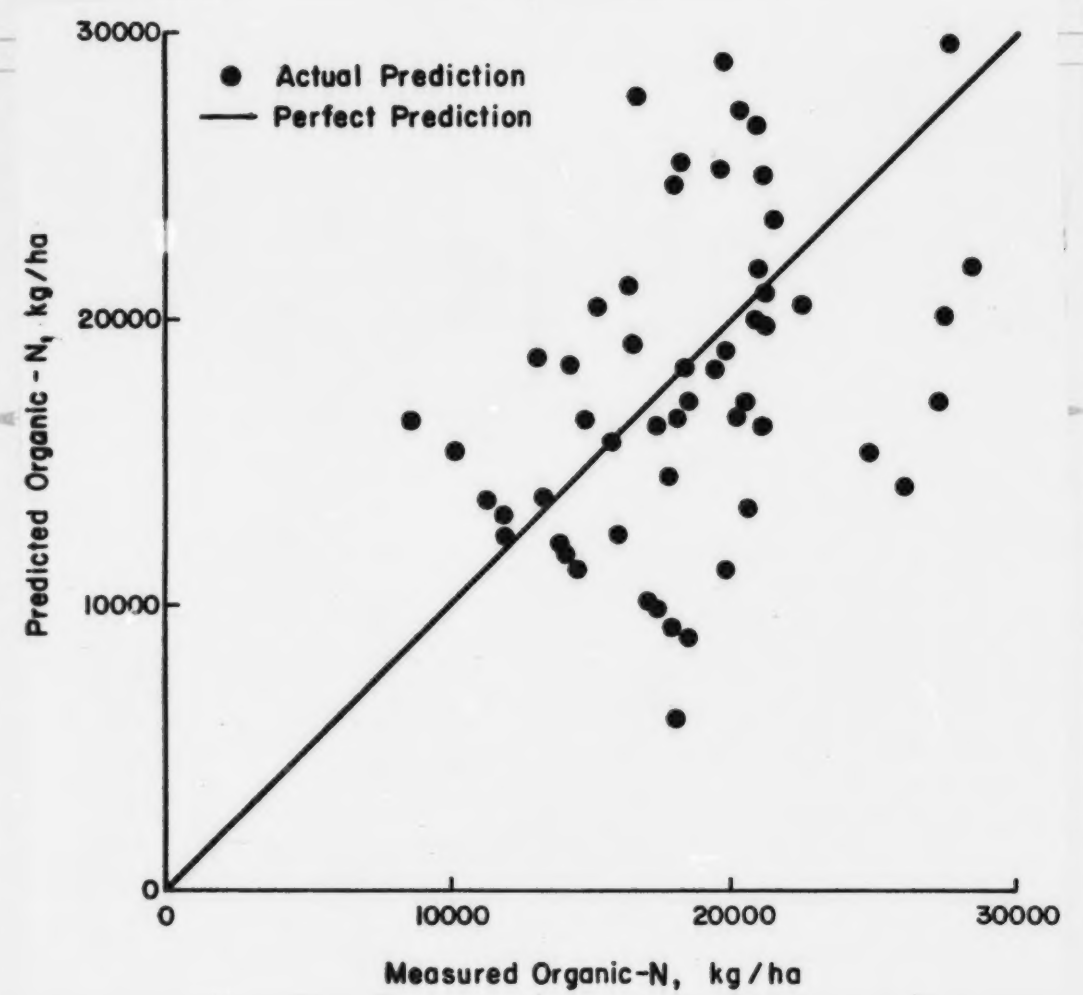

Figure 25. Comparison of measured and predicted amounts of Org-N in the root zone.

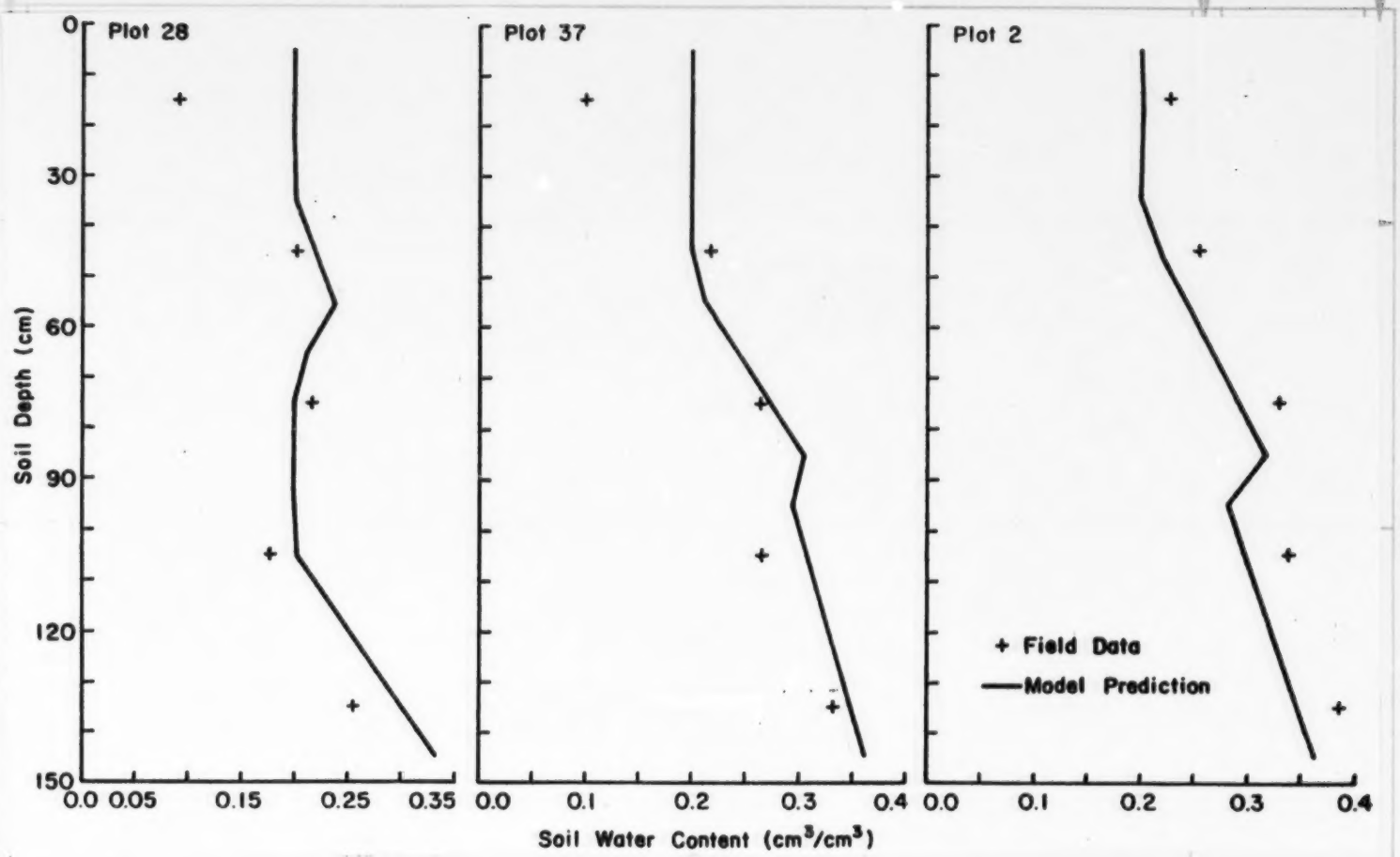

Figure 26. Comparison of measured and predicted soil-water profiles for three typical plots.

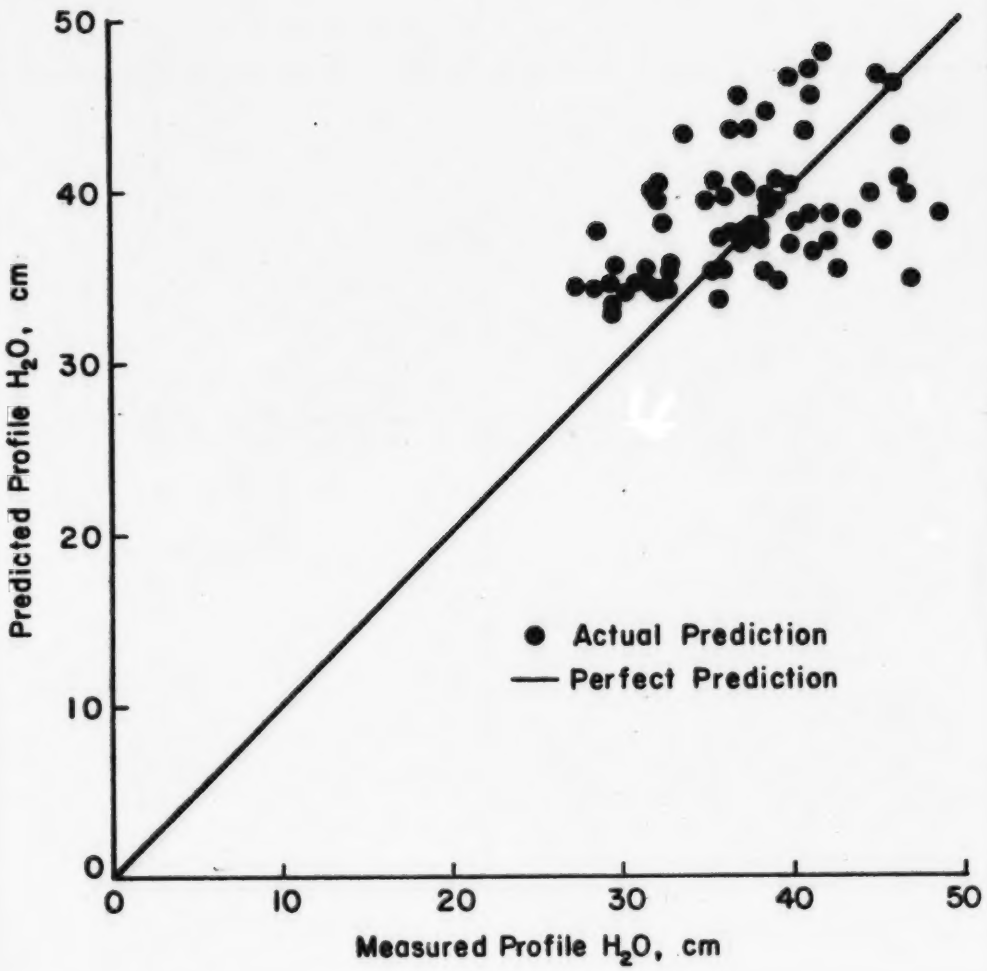

Figure 27. Comparison of measured and predicted amounts of soil-water in the root zone.

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SOIL CARBON

The comparison between the measured TOC and predicted Org-C present in the root zone at the end of the season is shown in Figure 28. It can be seen that the model underpredicted the amount of C present in almost every case. However, the average absolute deviation was 24,200 kg/ha, which amounts to an average absolute error of only 18 percent for the typical plot containing an average of 131,650 kg/ha. Thus, it may be concluded that the model can predict Org-C content quite well using only typical C transformation rate coefficients.

PLANT NITROGEN UPTAKE

Corn was planted near May 15 each year of the study. The crop growing season (TMAX) was 123 days. The maximum N uptake (TNU) was assumed to be 220 kg-N/ha, and the final rooting depth was taken as 120 cm. The minimum solution concentration below which NO_3-N and NH_4-N could not be absorbed by the plant roots was chosen to be 10 mg/l.

A comparison between the measured plant N uptake and that predicted by the model is shown in Figure 29. The correlation is considered satisfactory, especially in light of the empirical nature of the uptake submodel. The average absolute deviation from the measured values was calculated to be 26 kg-N/ha.

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The greatest difficulty was encountered in predicting uptakes of less than 100 kg-N/ha. It is possible that micro-nutrient deficiencies occurred in the last year on some of the plots which received manure only at the start of the study. The model considers yield reductions due only to N deficiency or water stress, so yield reduction due to any other factor would result in overpredicting the N uptake. The previously discussed problem in predicting the correct NO_3-N concentration in the upper 60 cm of soil was no doubt responsible for many of the cases in which the model underpredicted the amount of crop N uptake. The model has predicted the relative magnitude of N uptake quite well, however, and appears quite suitable for use in lieu of the complex plant and root growth models needed to more accurately describe N uptake.

POTENTIAL EVAPOTRANSPIRATION

From the nearly three years of daily measurements of climatic parameters and alfalfa water use from the lysimeters, data fitting the conditions necessary for E_{tp} were extracted. Climatic data were averaged over three-day periods to smooth any unknown variations and utilized in the Penman equation to calculate E_{tp}. These data were then compared to the lysimeter measurements as an indication of the model adequacy. The results are shown in Figure 30 for the 35 three-day periods in consecutive order. Figure 31 shows the aggregation of these results without regard to the temporal distribution of the data.

The Penman model was calibrated by Boonyatharokul (1979) using 1977 and 1978 data. The model fit equally well for the 1979 data, thereby giving it at least partial verification. An extensive analysis of the data-model variations

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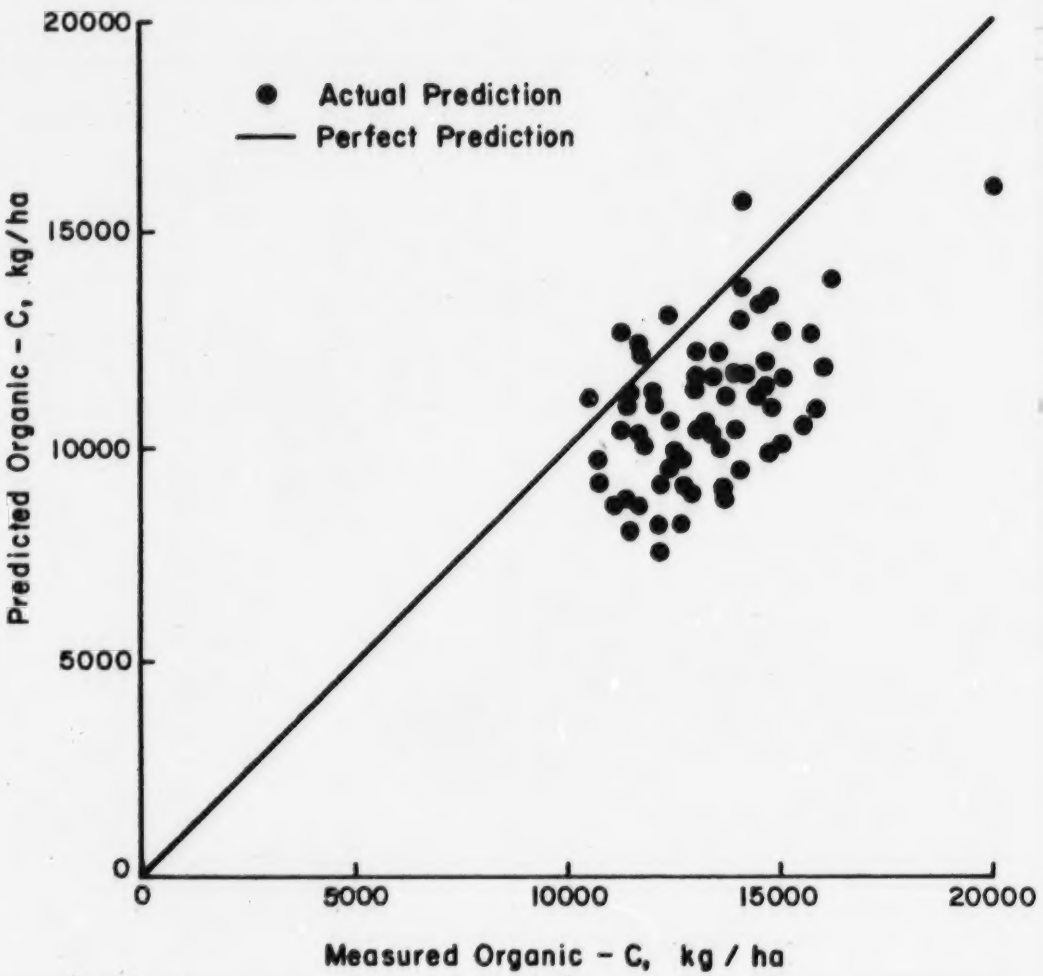

Figure 28. Comparison of measured TOC and predicted Org-C in the root zone.

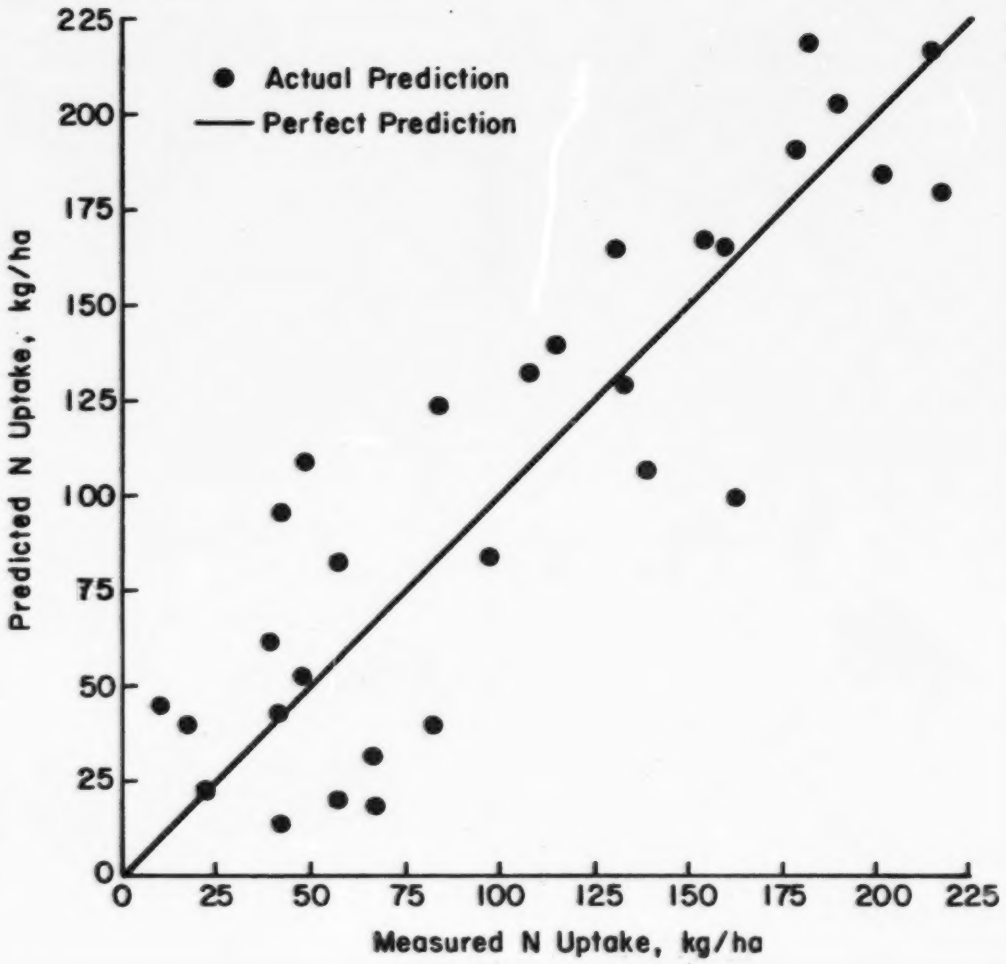

Figure 29. Comparison of measured and predicted plant N uptake.

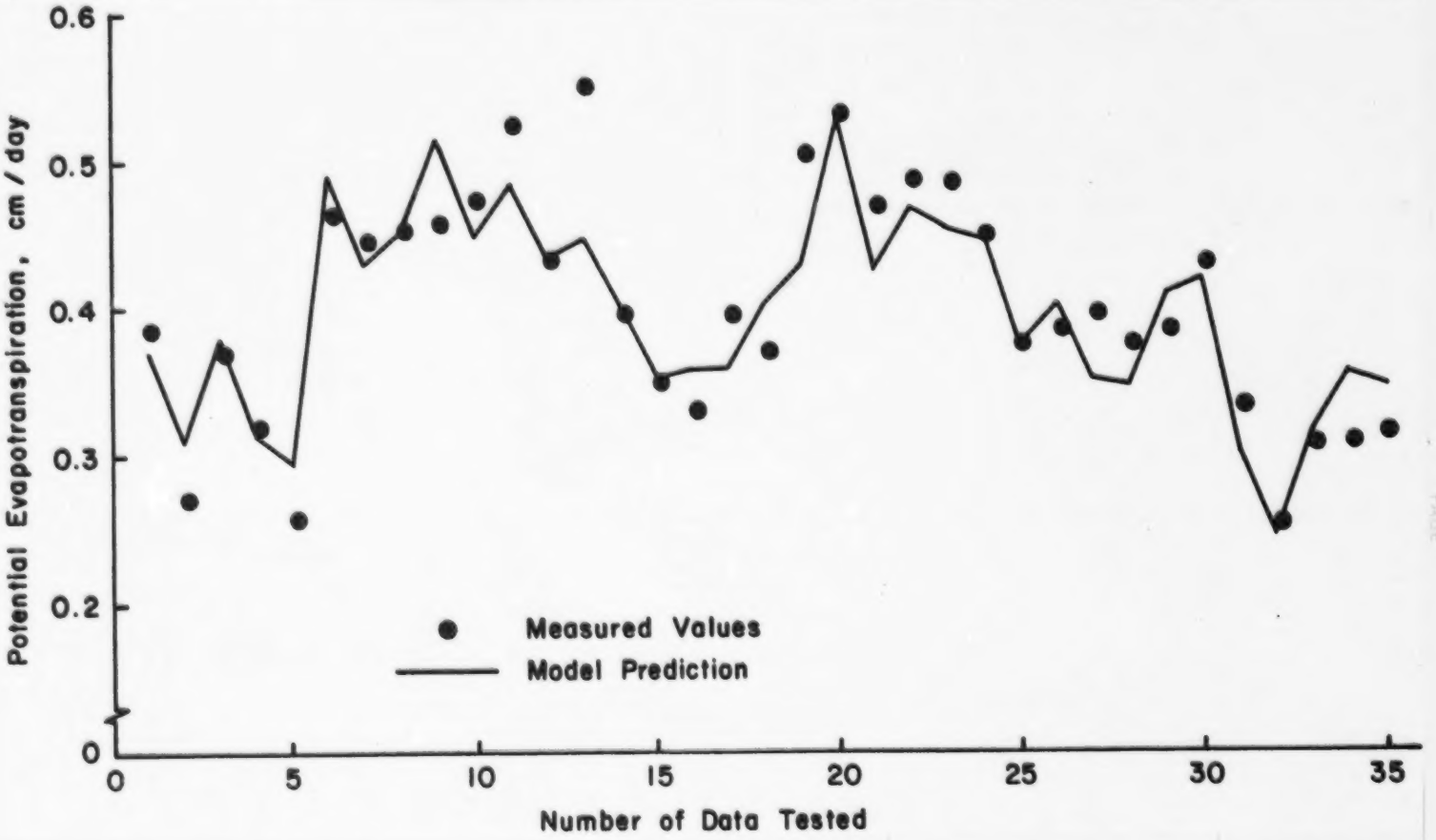

Figure 30. Comparison of Penman prediction of E_{tp} and lysimeter measurements over the period of the project.

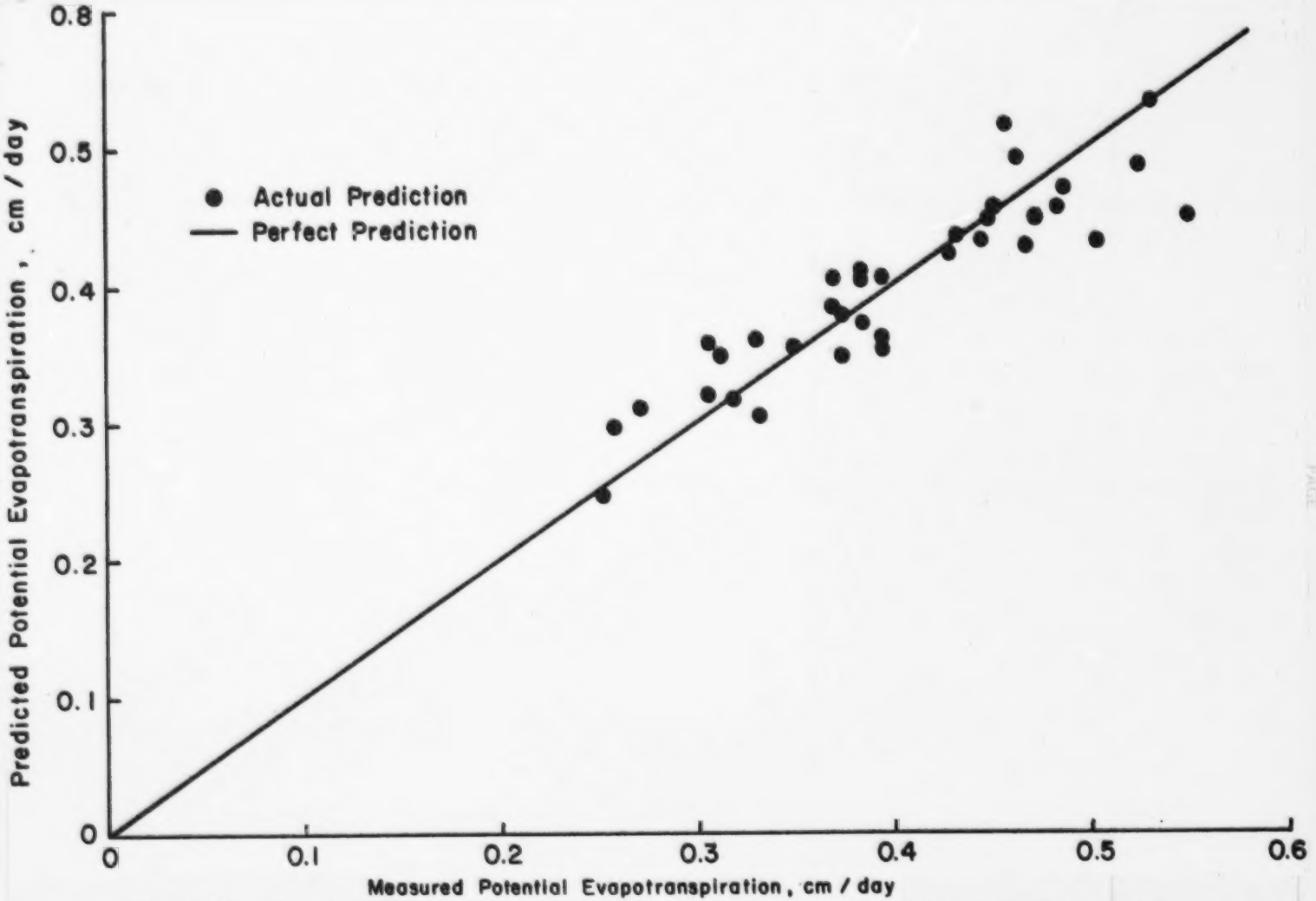

Figure 31. Predicted and measured E_{tp} during the project period based on data scale.

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was made to determine the best time interval for using the Penman method. It was found that cumulative evapotranspiration could be predicted with an accuracy of about 10 percent after two or three of any series of three-day time periods. Accuracy was improved by aggregating on a five- or seven-day basis. Thus, it can be concluded that in using even a sophisticated model like the Penman equation, time increments of three to seven days are more appropriate than daily estimates.

SUMMARY

Rao et al. (1980) details the calibration and verification of individual components of the simulation model. The results of this study summarized above indicate the model response in aggregate. Given the large natural variability in the field data, the model performance should be considered very good. The simplifications made to provide a more usable analytical tool appear well justified when viewed along with field data variance.

For studies dealing with animal manure application on irrigated lands, the model effectively represents the major transport and transformation processes. It can be improved by a more rational adjustment of soil and manure Org-N mineralization in the upper soil layers. Field data should particularly emphasize sampling in the top 30 cm in order to better define important initial conditions.

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SECTION 6

IRRIGATION AND WASTE LOADING MANAGEMENT

INTRODUCTION

Several modifications were made to the original computer code developed by Rao et al. (1980) in order to study the consequences of various irrigation and manure disposal practices on the N system. It was assumed that most transformation and transport processes occurred during the April 15 to October 1 period when the average temperature remained above freezing. During the winter months, these processes were assumed to stagnate based on examination of the field data. The code was then adjusted to repeat seasonal calculations over a period of about ten years using end of season conditions as new season input. One exception to this procedure involved re-initializing soil moisture levels to field capacity each year to reflect the effects of winter precipitation.

Long-term average climatological conditions were used to develop a temporally distributed function for E_{tp}. Planting dates for the corn used in the analysis were defined on May 15, and the crop was harvested September 15 for fodder. Thus, the model was modified to simulate conditions before and after the growing season. In order to provide dates and amounts of irrigation, an irrigation scheduling routine was added to the model. This scheduling routine programs irrigation when the weighted average soil moisture depletion reaches levels set by the user. The efficiency of the irrigation was computed as a function of time since the beginning of the irrigation season.

Following code revisions, a large array of base conditions, irrigation practices, and manure loading rates were evaluated over extended periods of time. In most cases, the time interval was eight to ten years or until the conditions in the first two meters of the soil profile reached steady-state conditions. An analysis was also made of the effects of salts in the animal manure on soil and leachate salinity levels. The results of these simulation runs are divided into four areas: (1) the steady-state condition; (2) the effects of irrigation practices; (3) manure loading alternatives; and (4) soil salinity. Before detailing these results, it is useful to summarize the general conditions studied.

Initial Organic Matter Conditions

The initial levels of organic matter in the soil profile significantly effects the quantities of N species in the system. The Grand Junction soil at the test site contained relatively high levels of organic materials throughout the soil profile as described earlier. To test the effects of management

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practices on another soil condition, the simulation runs were conducted on the Grand Junction soil with 20 percent of the actual organic matter content. This level of organic matter was approximately the same as the condition utilized by Rao et al. (1980) to demonstrate the model.

Irrigation Practices

The application of irrigation water was characterized by two indices: (1) frequency, and (2) efficiency. The irrigation frequency was based on the ASMD values of 0.6, 0.3, and 0.15 to be consistent with the experimental design. Values corresponding to the IRF parameter defined in Section 4, and will be described in more detail in a subsequent paragraph.

Animal Manure Loading Alternatives

In addition to investigating annual loading rates of 100, 200, 400, 800, 1,600, and 3,200 kg-N/ha, applications for an every second and third year schedule were evaluated. Again, these treatments were consistent with the experimental design. More detail will also be given concerning the part of the analysis in a later paragraph.

Manure Salinity Impacts

Concern is often voiced about the effects of the salts contained in animal manures on soil salinity levels which directly impact crop production. Cl^- loadings in proportion to the manure NO_3-N content were included in the simulation runs as an indication of the salinity effects.

THE STEADY-STATE CONDITION

The soil profile is always in a dynamic state. Some processes, such as infiltration of irrigation water or precipitation and evapotranspiration, change rapidly during a typical day in the growing season. The redistribution of water in the soil profile is a slower process and may take three to five days to approach an equilibrium condition. The movement of soluble chemicals is a somewhat slower process because of interactions with soil materials and dispersion effects.

It is improper to assume that the effects of manure disposal on irrigated lands will be quickly exhibited in the soil profile and groundwater. The transformations of manure and subsequent N and C materials are much slower processes than those mentioned above. If the monitoring effort associated with a disposal system is not maintained for a substantial interval, it is likely that the effects on groundwater quality will be underestimated.

An examination of this problem was made for the normal Grand Junction condition. Irrigation efficiencies and frequencies were based on typical valley-wide conditions, and a 2 m depth of soil. The model was then run over a 10 to 15 year period for annual spring manure loading rates of 200, 800, and 3,200 kg-N/ha. Figure 32 shows the amount of NO_3-N and NH_4-N leached below the 2 m depth as a function of time. The leaching rates increased from a value of about 50 kg-N/ha/yr without manure applications to constant values

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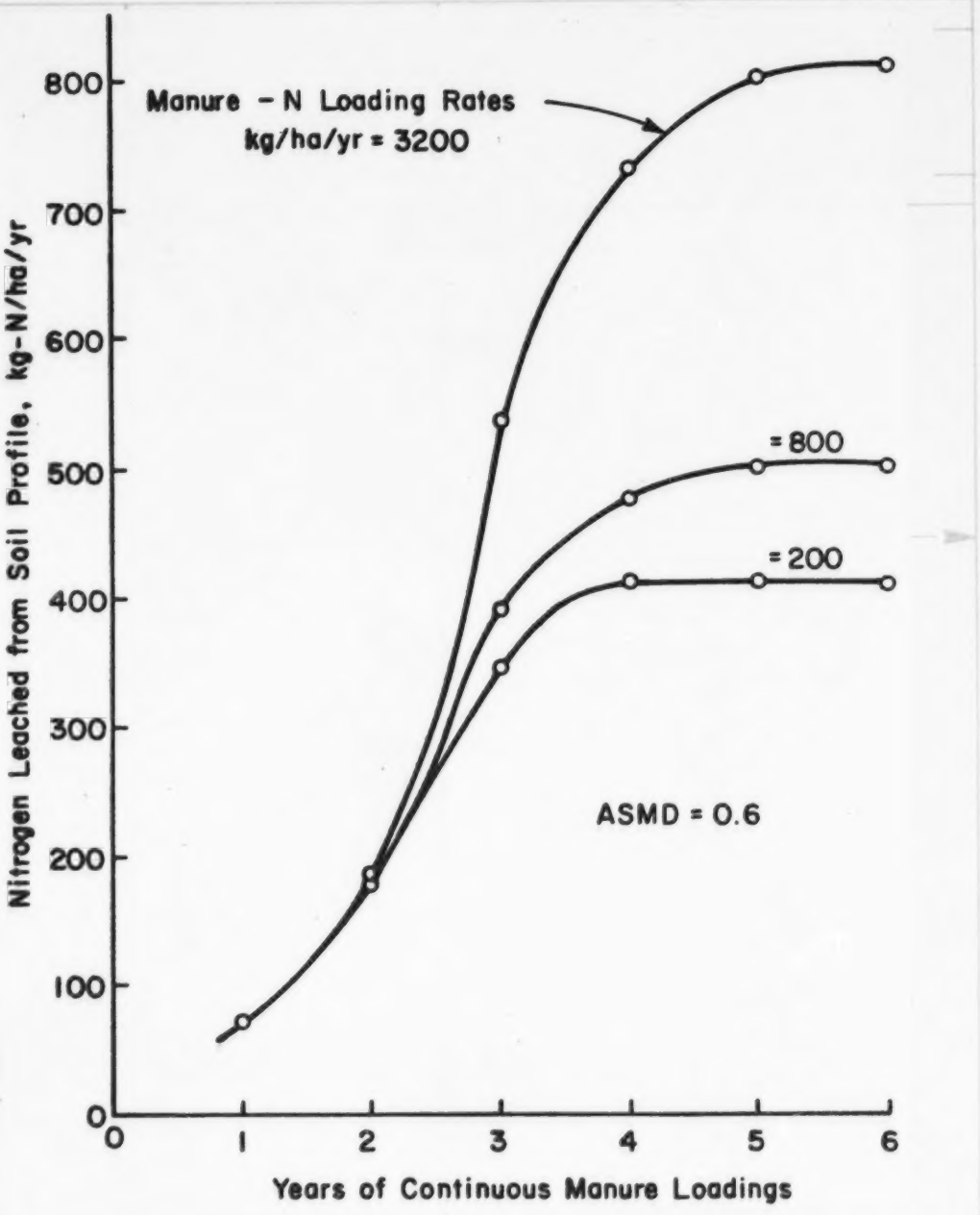

Figure 32. Build-up of N leaching losses following annual manure applications under normal Grand Junction conditions.

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of 412, 505, 815 kg-N/ha/yr, respectively. The lower application rates tend to stabilize more rapidly than the heavier rates. The 200 kg-N/ha/yr rate reached a constant leaching rate after about four years of treatment, whereas the 3,200 kg-N/ha/yr rate required about six years to produce a steady effect at the 2 m depth.

These results were of course simulated rather than actual results. However, monitoring of drainage NO_3-N concentration during the three years of this study did not indicate significant increases in concentrations. Since the average drainage system depth was near 2 meters, it can be concluded that the simulated results are realistic.

EFFECTS OF IRRIGATION PRACTICES

In the results that follow, it will be clear that management of the irrigation system is very important in controlling the potential NO_3-N contamination of groundwater under disposal sites. During the formulations of this research, several effects were thought possible based on the reports of other investigations. The two indicators of irrigation management that were thought to reflect those effects were the E_a and the application frequency.

Irrigation Application Efficiency

A mistake is often made concerning the change in IRF that occurs from irrigation to irrigation. It is common to represent each irrigation as having a constant or average value of IRF which depends on the soil, irrigator skill, and system design. This assumption leads to exceptionally biased results when applied to the biochemistry of the soil profile. Following planting, the soil in the plow layer has a significantly lower bulk density and greater particle aggregation than later in the growing season. Infiltration rates are much higher in most soils. The irrigator is concerned with lateral wetting to maximize germination, and consequently this amount of water applied is much greater than the quantity required to refill the root zone. Typical IRF values in the Grand Junction area and throughout the western United States for the first irrigation are on the order of 0.30. As an irrigation season progresses, soil infiltration rates decrease due to the consolidation of surface soils, crop roots extending deeper in the soil, evapotranspiration rates increase, and the irrigator is more concerned with refilling the root zone than wetting the seed bed. The result is dramatic increases in IRF. Many surface irrigation systems achieve IRF values of 0.80 to 0.95 following two to three irrigations. While the often quoted IRF value of 0.50 is true on a seasonal basis, it poorly reflects the conditions actually occurring.

The IRF in the simulation model was simulated by the following equations:

$$IRF(i) = 0.1625 + i(0.1375);\ i \leq 4 \qquad (31)$$

and

$$IRF(i) = 0.85;\ i > 4 \qquad (32)$$

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where i is the number of irrigations since planting. The IRF value calculated by Equations 31 and 32 match those typically measured in the Grand Junction area and may not be representative of other areas except in trend.

Using the normal site condition, leaching and denitrification losses resulting from the range of annual manure loadings were simulated over the period of years required to reach "equilibrium" at the 2 m depth. These tests were made for IRF values described by Equations 31 and 32 as well as an "improved" condition. The improved condition was simply to reduce the applied depth during the first irrigation by one-half (IRF increased to $\sim$ 0.67). All other irrigations followed Equations 31 and 32. The results are shown in Figures 33 and 34. Conditions are also shown for the case in which the natural organic matter content in the soil profile was defined at 20 percent of the normal condition and these results will be noted later.

For the normal condition, leaching rates shown in Figure 33 increase approximately linearly from about 400 kg-N/ha/yr to over 700 kg-N/ha/yr. By improving only the first irrigation, these rates are decreased by about 50 percent. In other words, the emphasis of irrigation water management should be on controlling the efficiency of the first and possibly second irrigations.

Figure 34 indicates that improved irrigation practices (higher IRF) actually increases the denitrification losses and thereby improves the soil system as a disposal site. The increase in denitrification rates was due primarily to an increase in NO_3-N levels since less is leached from the profile. It can be seen, however, that denitrification rates were much less sensitive to irrigation efficiency than the transport processes.

Irrigation Efficiency

There are indications in the literature that maintaining soil moisture at various levels could have significant effects on denitrification (Meek et al., 1974). The effect therefore would reduce the leaching losses of NO_3-N and NH_4-N. In the field investigations, irrigations were initiated when the available soil moisture had been depleted by 60, 30, and 15 percent, respectively. To test the effects of average soil moisture levels, the normal site condition receiving spring manure loadings over extended periods were simulated at these three values.

The results of irrigating at different frequencies are shown in Figure 35. Included in the figure is the leaching fraction on an annual basis. One minus the leaching fraction is the average value for IRF. It can be seen that changing the frequency reduced N leaching substantially, but the effect is primarily one of irrigation efficiency rather than frequency. The effects of the soil moisture level were not significant using the simulation model. However, the frequency of applying irrigation water was important if viewed from its actual effect on IRF. The wetter soil condition, found under more frequent irrigated systems, exhibited lower infiltration characteristics and therefore provides a more manageable irrigation system.

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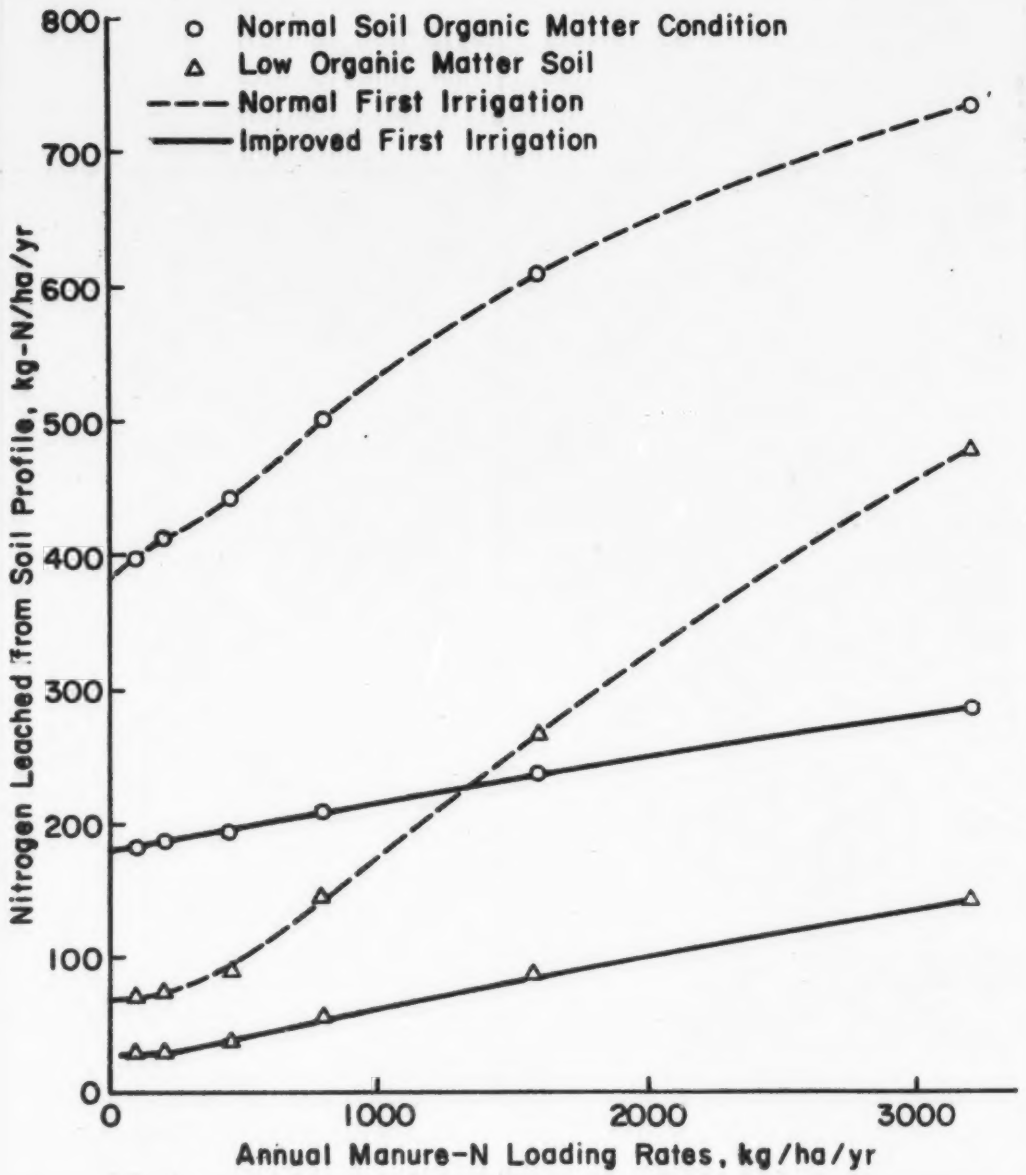

Figure 33. Comparison of N leaching rates as functions of manure loading rates for normal and improved first irrigation efficiency.

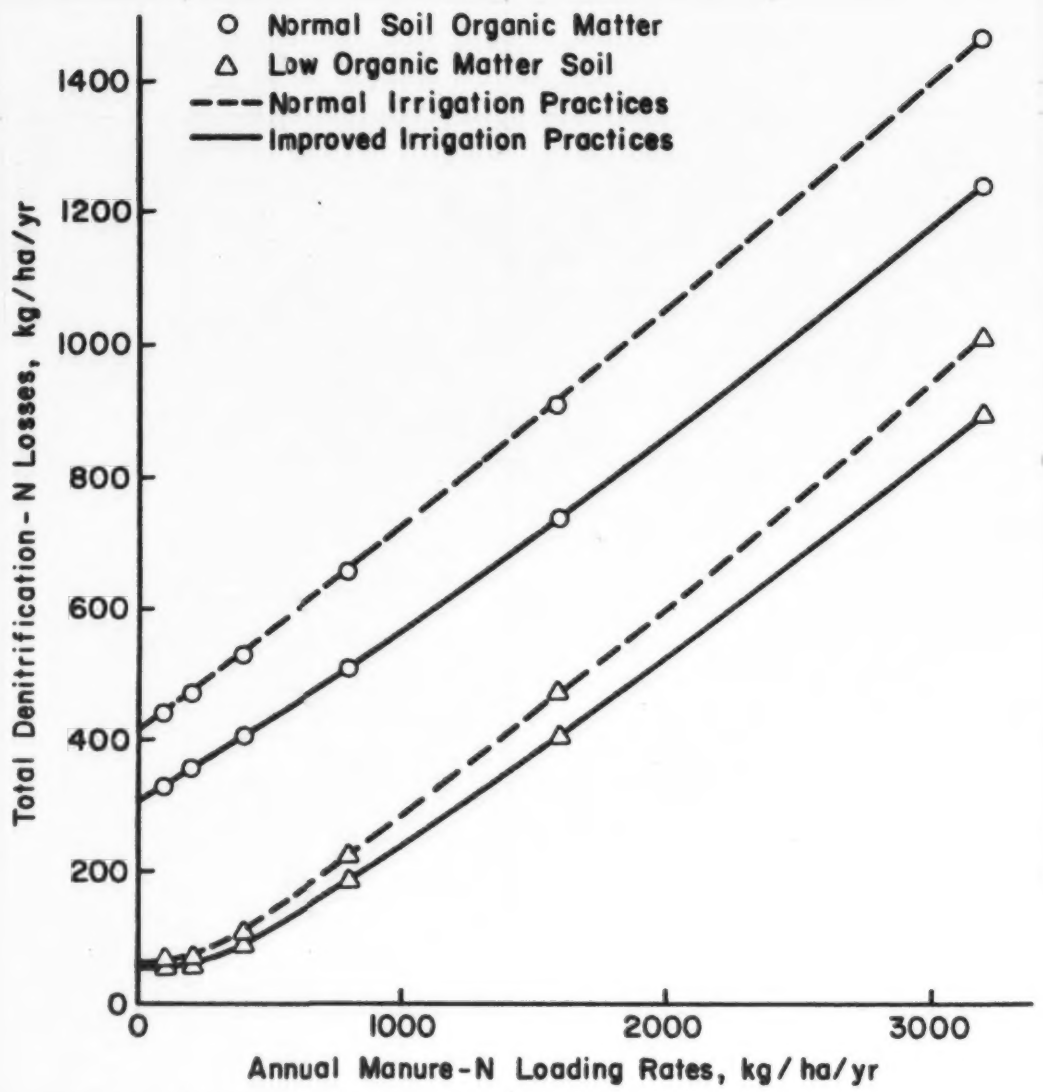

Figure 34. Comparison of denitrification rates for normal and improved irrigation practices.

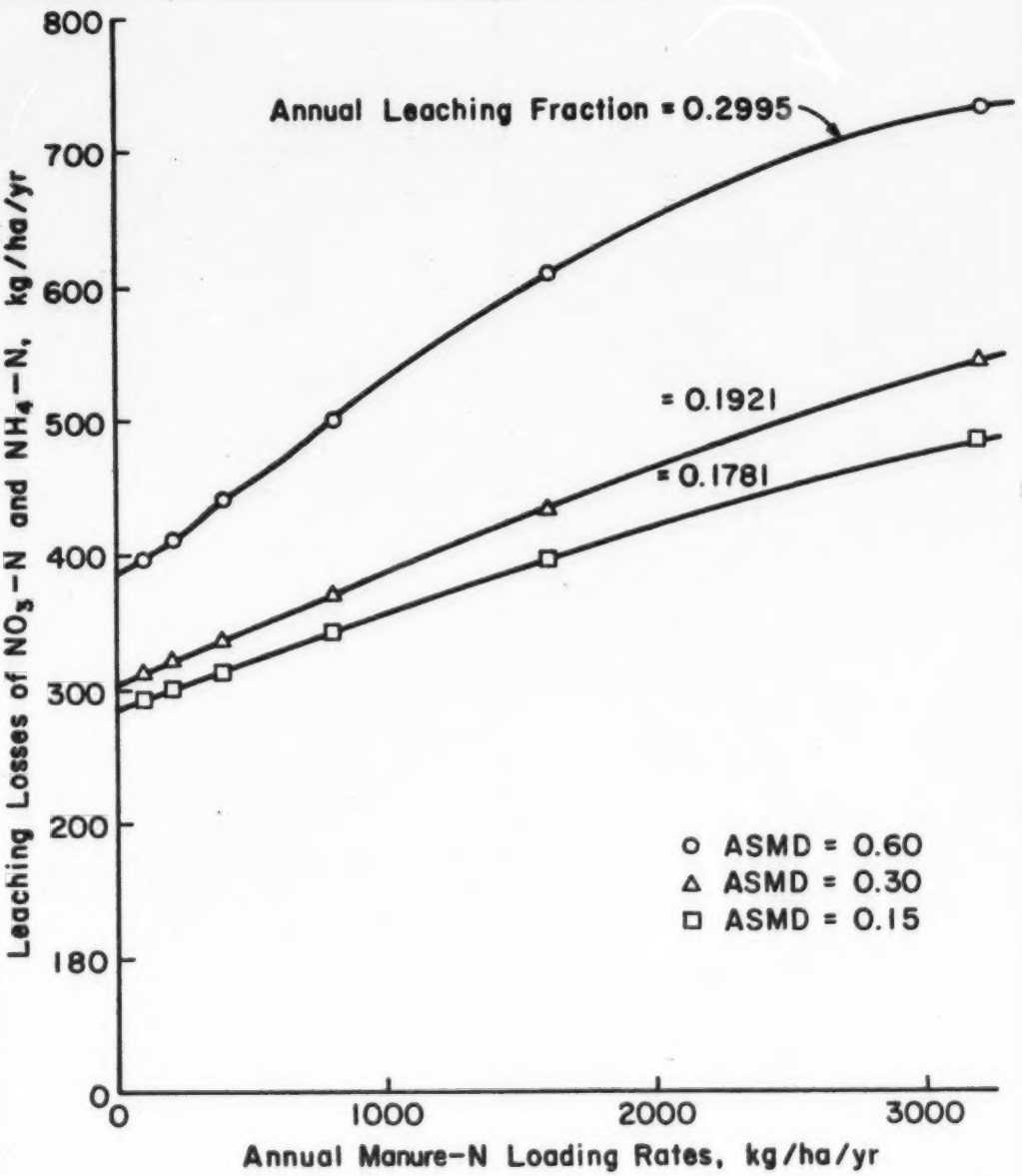

Figure 35. NO_3-N leaching rates as functions of manure loading rates and irrigation frequency.

ANIMAL MANURE LOADING PRACTICES

In Figures 33 and 34 a definite effect on N leaching and denitrification was evident from the level of soil organic matter present at the time the manure disposal was started. A similar loading program on a soil of low initial organic content produces less potential N contamination of the groundwater than a soil naturally high in organic matter. The differences, however, are not in the same proportion as the initial organic conditions. Figure 33 for example indicates N leaching losses associated with a 3,200 kg-N/ha/yr loading rate varied from 730 kg-N/ha/yr to 475 kg-N/ha/yr for the normal 20 20 percent of normal organic matter conditions, respectively. Thus, a five fold change in soil organic matter produced less than a two fold change in N leaching losses. The effects were approximately the same for the denitrification process (Figure 36). Figure 37 shows the effects of irrigation frequency on leaching losses for the reduced organic matter soil.

It can be concluded that manure loading rates and irrigation practices can be designed in conjunction with soil conditions to manage the downward flux of N. For instance, under normal test site conditions, a downward N flux can vary from about 800 kg/ha/yr to less than 200 kg/ha/yr. If a lower organic soil is present, the range is more on the order of 500-50 kg/ha/yr. Examination of Figure 37 shows the maximum annual loading rate that should be allowed for targeted N inputs to a groundwater basin. Other important waste management practices can be evaluated with the model where conditions are different or other practices are of interest.

In addition to loading rates, another manure management alternative is to apply the manure in varying annual cycles. Following the experimental design, the consequences of applying the wastes annually, every second year, and every third year were studied. To present these results in a somewhat different light, the ratio of N leaching losses to denitrification losses for the three alternatives are plotted in Figure 38. The conditions are the unimproved normal Grand Junction conditions.

When manure was applied each year, the leaching-denitrification ratio was greater than one until the annual loading rate was about 800 kg-N/ha/yr. Then, the denitrification losses are larger than the leaching losses. When the manure was applied every second year, the transition occurs at approximately 2,100 kg-N/ha/yr. For loadings of every third year, the leaching losses are always substantially higher than the denitrification losses. It is important to note that when the total N leaching was evaluated, the differences between the three treatment levels were less than 10 percent. Thus, the effect shown in Figure 38 is due to the changes in denitrification rates. These results lead to an interesting conclusion. The use of an irrigated soil as a manure disposal site is significantly enhanced by applying the manure annually rather than less frequently.

MANURE SALINITY

Table 1 shows that the beef manure used in this study contained about 2.2 percent total N. Individual cations and anions ranged from about 3 percent for Ca to 0.7 percent for Na. An indication of the impacts of manure salts in

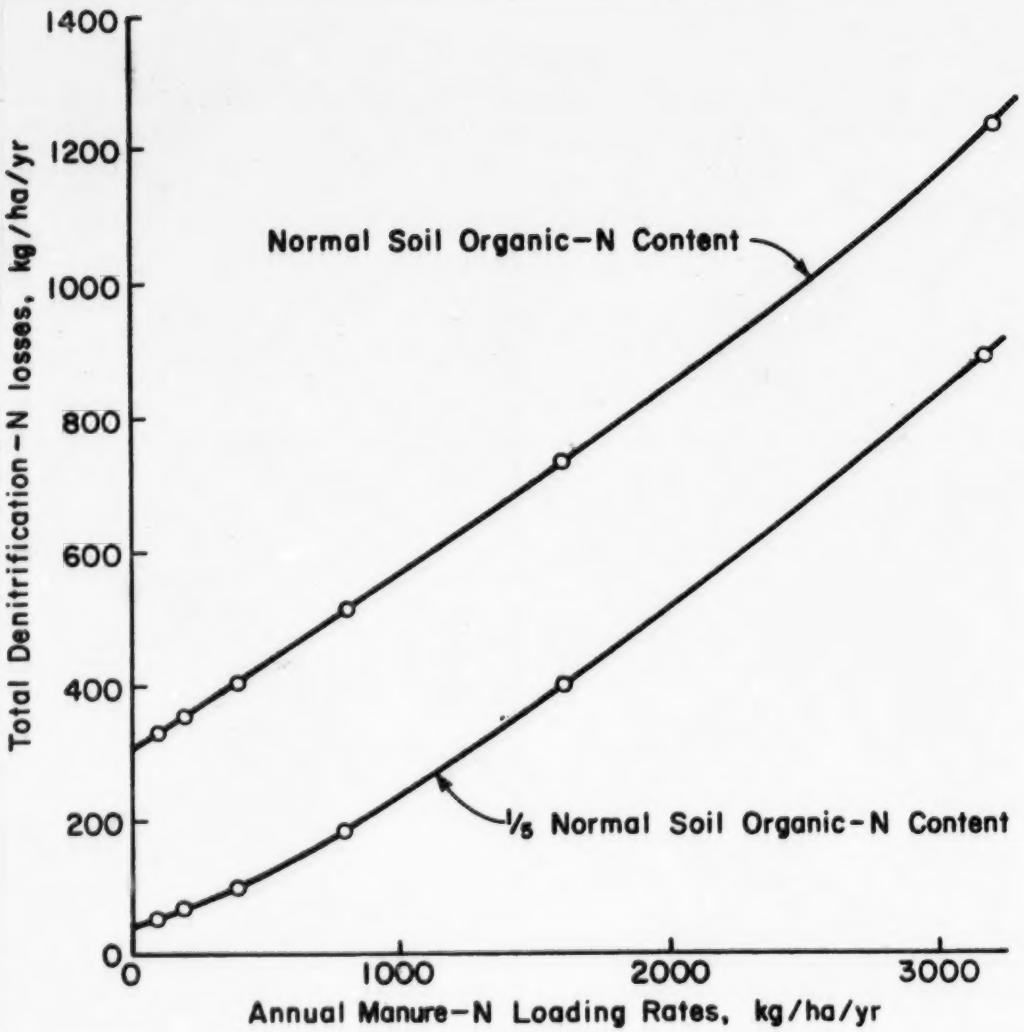

Figure 36. Denitrification losses for the two soil conditions as functions of manure loading rates. (Improved irrigation practices are assumed).

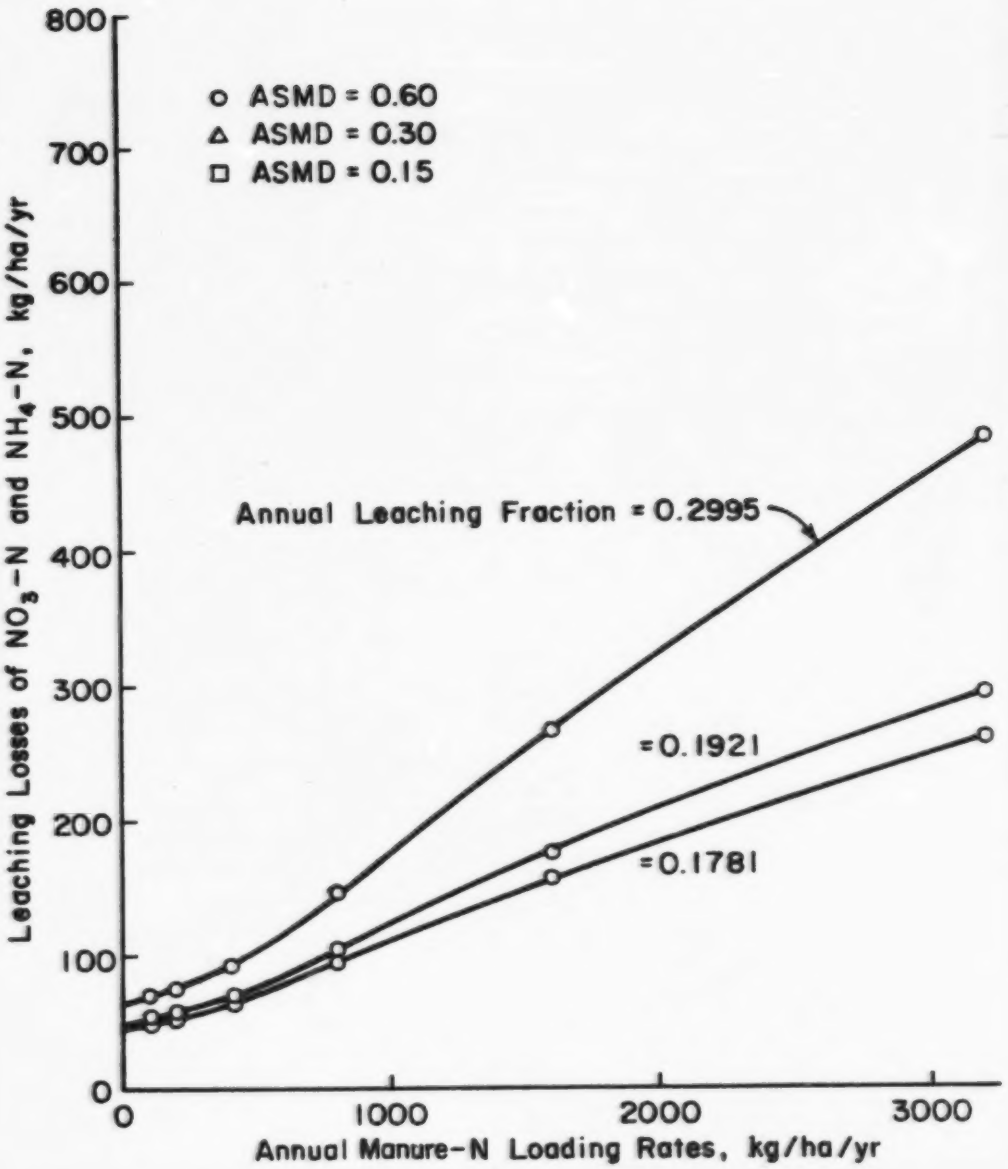

Figure 37. NO_3-N and NH_4-N leaching rates as functions of ASMD and manure loading rates for a soil with 20 percent of the initial Grand Junction organic matter content.

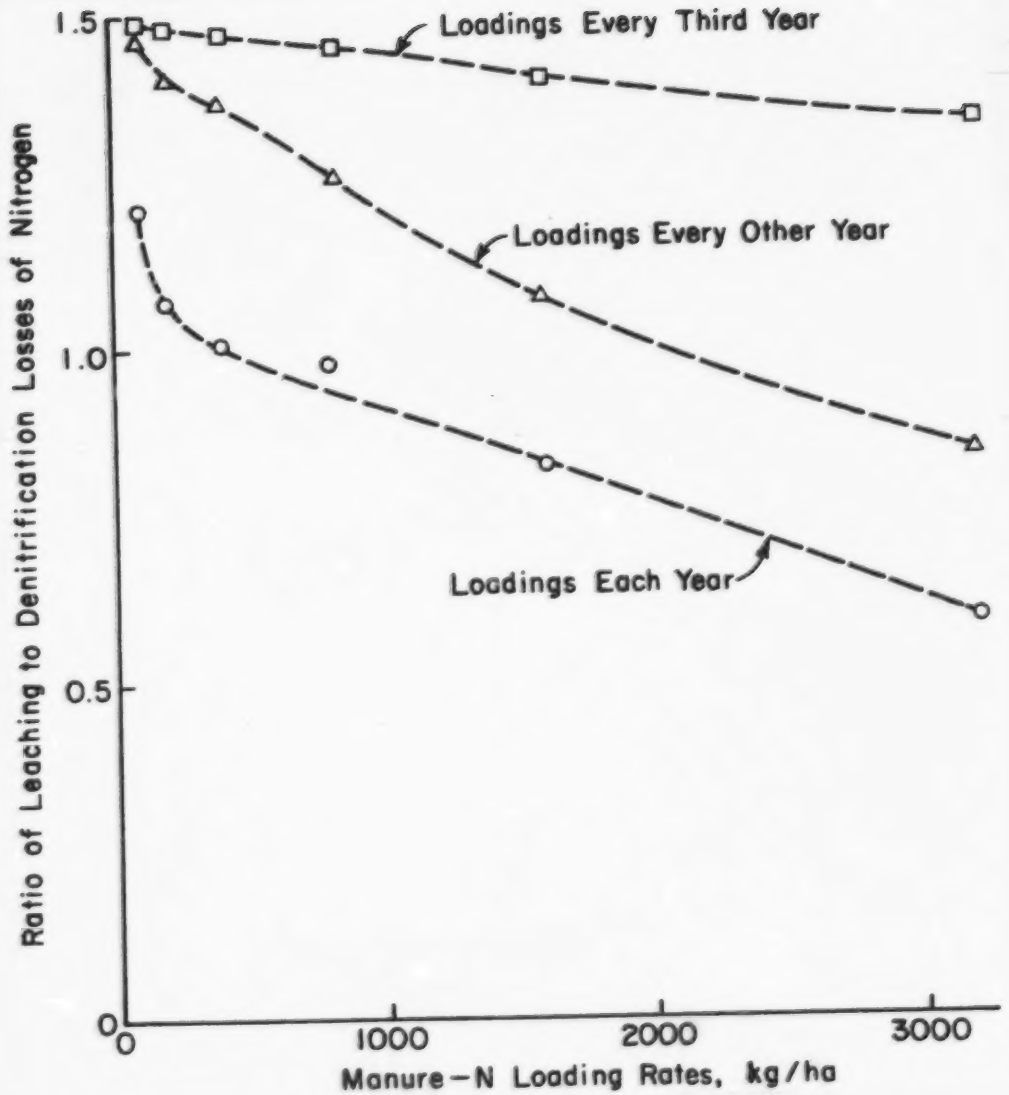

Figure 38. The effect of variable intervals between manure applications on the ratio between denitrification and leaching.

the soil profile provide an interesting contrast to the N system. Under normal site conditions a manure loading rate of 1,600 kg-N/ha/yr was simulated in the soil until steady conditions were approached at a depth of 2 m. The model was used to evaluate the movement of Cl^- since this anion could be classed as indicative of how the total salinity system would react if few of the solutes exchanged with the soil matrix. To accomplish this in a N model, all transformations were prevented and the loading was modified to reflect Cl^- concentrations. For the 1,600 kg-N/ha/yr manure loading, the Cl^- loading would be about 1,168 kg/ha/yr. With the N transformations stopped, the NO_3 ion was assumed to behave like the Cl^- ion.

The results are shown in Figure 39 for two of the investigated conditions, a normal and an improved irrigation efficiency. Existing soil salinity is omitted to show the effect of manure loadings. Under the typical situation, this addition of 1,168 kg/ha/yr of chloride to the soil surface had little effect until a depth of about 40 cm, then solute concentration surged upward to more than 800 mg/l at the 70 cm depth. The remainder of the profile showed the dampening effect on pulses supplied by previous manure additions. At 2 m, a reasonably steady concentration of about 600 mg/l was achieved. The most important observation was that the water percolation through the profile was sufficient to achieve a steady-state Cl^- balance in the soil.

When improved irrigation practices are implemented, the salinity picture changes drastically. A build-up begins close to the soil surface reaching a maximum value at about 60 cm and then declines to near initial conditions at the 2 m depth. This is not a steady-state condition. The width of the maximum Cl^- concentration expands until the profile reaches a uniform concentration in excess of 1,400 mg/l. The simulation run was terminated at the same number of years and evaluated for the normal case to show the time and magnitude factors.

It is obvious that salts in animal manure work against efforts to control N inputs to the groundwater. If the loading rates and manure salt concentrations are high, salt build-up in the soil will result from improved irrigation practices aimed at reducing N leaching. The irrigated system will quickly cease to support feasible crop production activities.

GENERAL MANAGEMENT GUIDELINES

Although a large number of irrigation and manure management practices were not evaluated, it was possible to identify several basic guidelines. Wherever the animal manure is applied to surface irrigated croplands, particular care should be given to the first watering. A major fraction of the seasonal water flux below the root zone stems from this irrigation due to higher than average infiltration rates and special considerations for seed bed wetting. The frequency of irrigations will increase denitrification losses from the soil profile, but the major impact will be in improving irrigation efficiencies.

Manure applications should be designed for the receiving soil since the fresh organic matter tends to accelerate the transformation of existing soil organics. A low organic soil appears to be capable of receiving higher

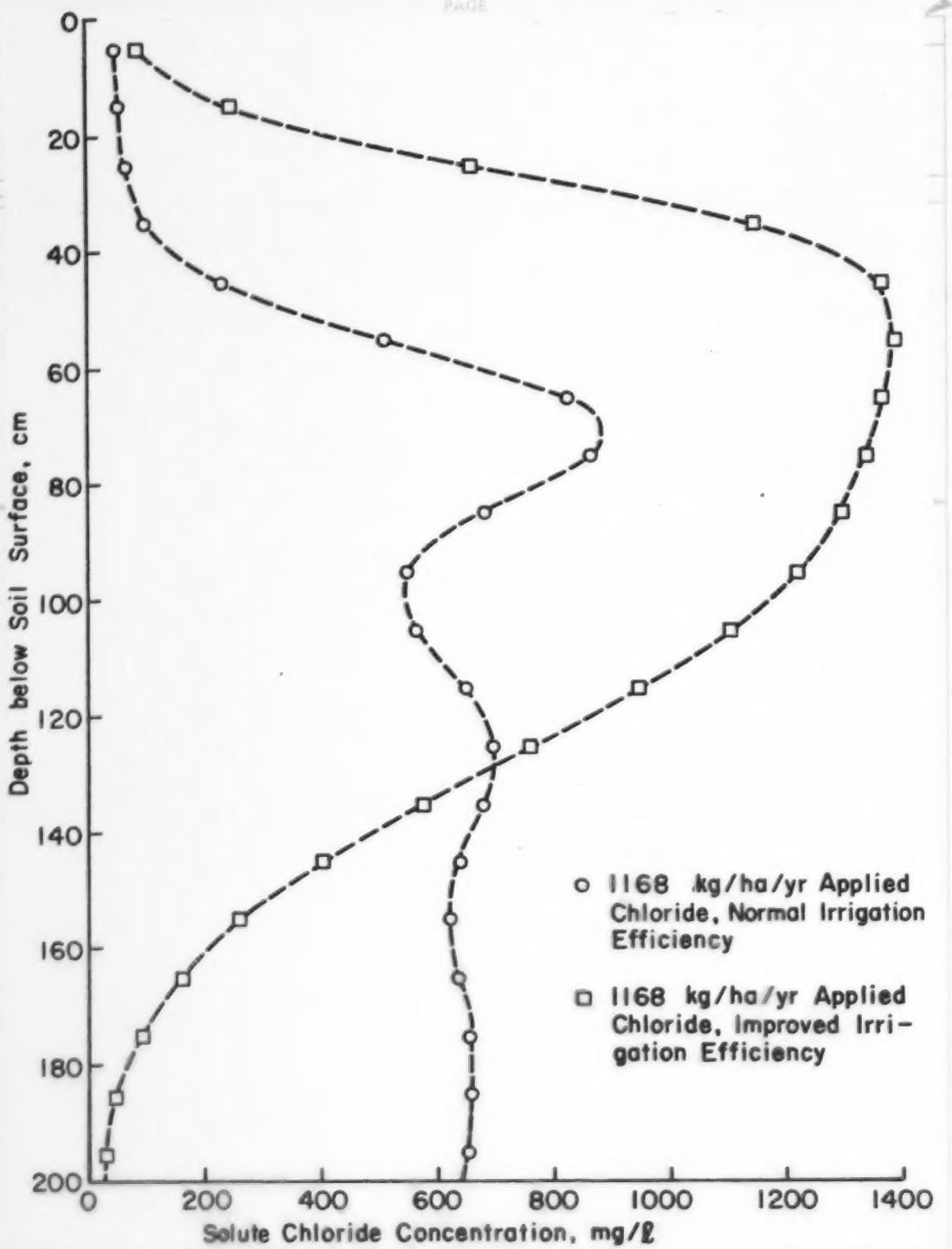

Figure 39. The distribution of manure derived Cl^- under normal and improved irrigation practices.

loading rates for a specific level of NO_3-N and NH_4-N movement toward the groundwater basin. Seasonal manure loadings are preferable to less frequent applications because denitrification processes are enhanced while N leaching does not appear to be significantly increased.

The salts in the manure must be considered a limiting factor in the loadings rates and the efficiency of water applications. It should be possible using an approach such as evaluated herein to determine the best disposal and irrigation regime for a particular soil condition, which will minimize groundwater contamination while preventing excessive salt build-up in the soil profile.

There tends to be a greater need with respect to time to monitor environmental quality as a basis for managing natural resources. This must be a long-term program in the case of potential pollutants applied to irrigated soil systems. Simulation models supported by field data collection to ensure their verification offertools for assessing alternative decisions.

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